Computational Modelling of Biomass Co-firing and Slag Formation under Air/Oxy-fuel Combustion in Furnaces

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Abstract

The use of biomass energy has significant contribution of the renewable energy employed today. Biomass fuels are treated as CO$_2$ neutral energy source. Besides the usage of coal in power plants, combustion technologies can be enhanced to further decrease the total costs of heat and/or power produced and to maximise safety and simplicity of operation. The need for innovation is driven by the wish to burn new biomass fuels such as energy crops, waste wood, and agricultural residues. Combustion of biomass provides severe challenges due to its non-homogeneous characteristics that need to be concentrated properly to have a solution in order to implement for further improvement. Hence, it is essential to model the combustion phenomena in order to discover potential problems that may occur during biomass co-firing and to mitigate potential negative effects of biomass fuels, including lower efficiency due to lower burnout. A detailed study is required to scrutinize the co-firing of coal and irregular shaped biomass particles.

To better understand the biomass combustion and thus improve the design for co-firing biomass in wall-fired furnace, it is important to consider several issues such as non-sphericity of particles, variation of sizes and variation of co-firing ratios. Utilizing of coal and biomass as a fuel increases the possibilities of slagging and fouling risk on the heat transfer surfaces, increase of corrosion risk, decrease of boiler capacity. But limited attempts are taken to investigate the slagging issue in the furnace. It is very important to know the amount and location of the slag as well as its dynamics. For designing and optimization of the slagging phenomenon, it is imperative to investigate the related process occurring inside the furnace.
The knowledge about the performance of coal/biomass co-firing, its emission, ashing, slagging and fouling is still quite limited. Experimental investigation is progressively used to determine the flow characteristics, temperature mapping, and emissions level for different combustion cases. Particle deposition, unburned carbon in ash and all other related issues as well as slagging require further research and development. Still, there are huge gaps in our knowledge about the thermal, chemical behaviour of such complex fuels. Further improvement of basic concept and different issues related to emission is important and thus modelling is necessary. Computational technique provides the opportunity to investigate in details, the combustion phenomena and contaminant development inside the furnace. But, the success of computational analysis largely depends on the proper numerical technique and the physical/chemical models employed. Therefore, for the reduction of the pollutant emission with available energy sources and technologies, a detailed analysis of the combination of biomass co-firing and slagging under oxy-fuel condition is interesting. Hence the main objective of the research work is to study the combustion of biomass fuel at different co-firing ratios under different oxidizing environments and to explore the fundamentals of slag deposition and flow characteristics in laboratory and industrial furnaces.

An initial investigation was conducted in a 0.5MWth combustion test facility (CTF) to predict the radiative and convective heat transfer performance of the combustion of 100% pulverised Russian coal under air and CO₂-rich oxy-fired environment. It was found that the flame temperature for the air-firing case was similar to RR72% case and the flame temperature increased with O₂ concentration and decreasing RR. The ignition condition was improved with enriched O₂ concentration and the radiative and convective heat flux was significantly manipulated by the recycled ratio (RR). A working range was suggested for retrofitting purpose which indicated that air equivalent radiative
heat flux could be obtained at a RR of ≈71% while an air equivalent flame temperature was observed at RR of 72%. Further studies validated the co-firing concept on the same furnace using coal and biomass having blending ratio of 20% and 40% under the operating conditions of recycled ratios (RR) 68%, 72% and 75%. It was predicted that due to increase of biomass sharing from 20% to 40%, the volume of the flame increases, but the flame stability and the peak temperature decreases due to higher volatile content in the biomass but the heat transfer was significantly manipulated by the biomass sharing with different recycled ratio. Compared to the working range of only coal combustion, co-firing of 20% biomass sharing suggested that optimum recycled ratio (RR) for flame temperature and radiative heat transfer to be closely matched with air-firing found at 71%, but for 40% sharing, a value of RR70% may be needed.

Based on the developed co-firing model, a critical analysis was conducted for firing straw particles having larger aspect ratio in a 30 kW semi-technical scale once-through swirl-stabilized furnace. This study highlighted the impact of co-firing straw on the burnout and CO emission characteristics under air and oxy-fuel cases. It was found that with 20% straw sharing, sensible performances were observed similar to that of 100% coal combustion. The CO levels are predicted to decrease in the downstream section during oxy-fuel combustion compared to air-firing flames due to O₂ availability. This study also indicated that size of particles plays a significant role to the overall performance. A critical analytical analysis was conducted to investigate the heating performance for straw particle of different sizes (100 µm, 330 µm and 1000 µm). The heating profiles show significant differences between the three particle sizes assuming isothermal temperature gradient and heating by both radiation and convection. The possibility of burnout of the larger straw particle size is less due to less residence time in air-firing compared to oxy-firing case. The burnout is reliably advanced during oxy-fuel combustion to 99.8% than air
Based on the previous study, the co-firing of woody type biomass concept was implemented in a 550MW tangentially fired furnace for possible retrofitting option. A series of investigation was conducted combining three different co-firing cases (20% biomass with 80% coal, 40% biomass with 60% coal and 60% biomass with 40% coal) under four different combustion cases (23% O₂/77% N₂, 25% O₂/75% CO₂, 27% O₂/73% CO₂ and 29% O₂/71% CO₂). With the increase of biomass sharing to 40% and 60%, peak flame temperature reduced significantly but improved burnout was observed for the improved oxy-fuel cases. A significant increase in unburned carbon in fly ash for the increase of biomass co-firing sharing was predicted. This study highlights the positive impact of changing the fuel ratio and combustion atmosphere on the boiler performance, underlining that minor redesign may be necessary when converting to biomass co-firing under air and oxy-fuel conditions.

A 3D slagging combustion model was developed for coal-firing in an industrial furnace under oxy-fuel combustion condition. This is a comprehensive slagging combustion model including gas-particle flow and particle-wall interaction sub-model. The model was validated considering a 3MWth small scale furnace for coal water slurry combustion. This model enables to determine the slag thickness deposited on the furnace wall during transient build-up. The deposited slag thicknesses for air and oxy-firing the cases were found in the range of 0-1.0 mm. It was found that due to higher viscosity and surface tension properties, the average molten slag velocity was 0.0001 m/s. Compared to air-firing case, slightly higher amount of slag was deposited in oxy-firing cases due to slower char oxidation rate. Later, slag model was applied in a 550MWth coal-fired furnace for determining the effects of slagging behaviour of the Brown coal combustion under oxy-fuel condition and notable performance of the furnace were explored.
List of Publications

Book chapter

Journal papers

Conference papers


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Declaration

This research work has been done by the candidate himself and does not contain any materials extracted from elsewhere or from a work published by anybody else. Also, the work for this thesis has not been presented elsewhere by the author for any degree. To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgement has been made. The publications resulted from this work are listed in the content.

Signature

Date: 01/07/2016
Dedicated to

My beloved parents and family members
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<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$A_c$</td>
<td>Pre-exponential factor ($s^{-1}$)</td>
</tr>
<tr>
<td>$A_v$</td>
<td>Pre-exponential factor ($s^{-1}$)</td>
</tr>
<tr>
<td>$A_p$</td>
<td>Cross sectional area of particle ($m^2$)</td>
</tr>
<tr>
<td>$C_D$</td>
<td>Drag coefficient</td>
</tr>
<tr>
<td>$C_{fu}$</td>
<td>Combustion model constant, (= 3.0)</td>
</tr>
<tr>
<td>$C_{pr}$</td>
<td>Combustion model constant, (=0.5)</td>
</tr>
<tr>
<td>$C_{(p,p)}$</td>
<td>Specific heat of the particle</td>
</tr>
<tr>
<td>$d_p$</td>
<td>Particle diameter ($m$)</td>
</tr>
<tr>
<td>$D_p$</td>
<td>Diameter of the particle ($m$)</td>
</tr>
<tr>
<td>$E_c$</td>
<td>Activation energy ($kJ \cdot mol^{-1}$)</td>
</tr>
<tr>
<td>$E_v$</td>
<td>Activation energy ($kJ \cdot mol^{-1}$)</td>
</tr>
<tr>
<td>$F_{idr}$</td>
<td>Drag force ($N$)</td>
</tr>
<tr>
<td>$F_{ig}$</td>
<td>Gravitational force ($N$)</td>
</tr>
<tr>
<td>$F_{react}$</td>
<td>Reaction force ($N$)</td>
</tr>
<tr>
<td>$G$</td>
<td>Production due to the buoyancy force</td>
</tr>
<tr>
<td>$h$</td>
<td>Heat transfer co-efficient</td>
</tr>
<tr>
<td>$K$</td>
<td>Turbulent kinetic energy ($m^2/s^2$)</td>
</tr>
<tr>
<td>$K_v$</td>
<td>Rate constant of devolatilisation</td>
</tr>
<tr>
<td>$m_{vp}$</td>
<td>Mass of particles at devolatilisation ($kg$)</td>
</tr>
</tbody>
</table>
\( m_{RFG} \)  
Amount of recycled flue gas

\( m_{PFG} \)  
Amount of product flue gas

\( m_p \)  
Mass of the particle (kg)

\( \min \)  
Minimum value of the operator

\( m_{s,i} \)  
slag mass,

\( m_{ex,i-1} \)  
Incoming slag mass flow rate,

\( m_{ex,i} \)  
Discharging slag mass flow rate,

\( Nu \)  
Nusselt Number

\( P \)  
Pressure (N/m\(^2\))

\( P_A \)  
Atmospheric Pressure (N/m\(^2\))

\( Pr \)  
Prandtl number

\( p \)  
Sum of partial pressure (N/m\(^2\))

\( P_g \)  
Partial pressure of oxygen at furnace (N/m\(^2\))

\( P_s \)  
Oxygen partial pressure at surface (N/m\(^2\))

\( q_{in} \)  
Syngas heat flux,

\( q_{ex,i} \)  
Discharging slag heat flux,

\( q_{ex,i-1} \)  
Incoming slag heat flux and

\( q_{out} \)  
heat flux at wall.

\( Re \)  
Reynolds number

\( R_{ep} \)  
Particle Reynolds number

\( R_p \)  
Radius of the Particle (\(\mu\)m)
\( \bar{r}_{fu} \)  Fuel consumption rate (kg/m\(^3\).s)

\( s \)  Path length

\( S_\Phi \)  Variable source, \( \Phi \)

\( S_{p\Phi} \)  Additional source term

\( S \)  Stoichiometric air/fuel ratio

\( T \)  Temperature

\( T_p \)  Temperature of the particle (K)

\( T_g \)  Gas temperature (K)

\( T_{pt} \)  Slag phase transformation temperature

\( \text{min} \)  Ash particle hitting the slag layer,

\( T_m \)  Ash particle temperature hitting the slag layer,

\( T_s \)  Temperature at solid slag and wall phase,

\( T_{ts} \)  Temperature at refractory and steel wall,

\( T_g \)  Flue gas temperature

\( T_w \)  Wall temperature

\( T_{(p,0)} \)  Instantaneous particle temperature

\( U_i \)  Velocity in the \( i \)th direction (m/s)

\( V_p \)  Velocity of the particle (m/s)

\( |u_{rel}| \)  Relative velocity (m/s)

\( V \)  product of volatiles at time, \( t \)

\( V_f \)  Ultimate product of volatiles
\[ x_i \] Spatial distance in the \( i \)th direction

\[ \bar{y}_{pr} \] Mass fraction of product (kg/kg)

\[ \bar{y}_{ox} \] Mass fraction of oxidizer (kg/kg)

\[ \bar{y}_{fu} \] Mass fraction of fuel (kg/kg)

Greek symbols

\[ \mu_t \] Turbulent viscosity (m\(^2\)/s)

\[ e \] Particle emissivity

\[ \tau_R \] Turbulent time scale (s\(^{-1}\))

\[ i_b \] Blackbody emissivity

\[ \Phi \] Variables

\[ \lambda \] Thermal conductivity (W/mK)

\[ i' \] Radiation intensity (W/m\(^2\))

\[ i'_{n+1} \] Total radiation intensity (W/m\(^2\))

\[ a_i \] Absorption coefficient

\[ \rho_g \] Density at gas phase (kg/m\(^3\))

\[ \rho_p \] Density at particle phase (kg/m\(^3\))

\[ \Gamma \] Diffusion coefficient of variable \( \Phi \)

\[ \sigma \] Stephan–Boltzmann constant (W/m\(^2\)K\(^4\))
\( \delta_l \)  liquid slag thickness
\( \delta_s \)  solid slag thickness
\( \delta_t \)  total slag thickness
\( \epsilon_p \)  Particle emissivity
\( \sigma \)  Stephen-Boltzman constant
\( \rho_p \)  Particle density
\( \lambda_g \)  Thermal conductivity
\( \rho_g \)  Density of flue gas
\( \mu_g \)  Viscosity of flue gas
\( g \)  Gravitational constant

List of abbreviations:

- **AASB**: Aerodynamically Air Staged Burner
- **AF**: Air-firing
- **CCS**: Carbon capture and storage
- **CFD**: Computational fluid dynamics
- **CIA**: Carbon in Ash
- **CLC**: Chemical looping combustion
- **CTF**: Combustion test facility
- **CWS**: Coal water slurry
- **DTRM**: Discrete transfer radiation method
- **DTG**: Derivative thermos-gravimetric
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>DTRM</td>
<td>Discrete transfer radiation method</td>
</tr>
<tr>
<td>RRD</td>
<td>Rosin-Rammler distribution</td>
</tr>
<tr>
<td>DDM</td>
<td>Discrete droplet method</td>
</tr>
<tr>
<td>ESP</td>
<td>Electrostatic precipitator</td>
</tr>
<tr>
<td>EBU</td>
<td>Eddy breakup model</td>
</tr>
<tr>
<td>FVM</td>
<td>Finite volume method</td>
</tr>
<tr>
<td>FC</td>
<td>Fixed carbon</td>
</tr>
<tr>
<td>FBC</td>
<td>Fluidized-bed combustor</td>
</tr>
<tr>
<td>FGD</td>
<td>Flue-gas desulphurization</td>
</tr>
<tr>
<td>FVM</td>
<td>Finite volume method</td>
</tr>
<tr>
<td>GCV</td>
<td>Gross calorific value</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse gas</td>
</tr>
<tr>
<td>IFRF</td>
<td>International flame research foundation</td>
</tr>
<tr>
<td>HC</td>
<td>Hydro carbon</td>
</tr>
<tr>
<td>HGOT</td>
<td>Hot gas off-take</td>
</tr>
<tr>
<td>IB</td>
<td>Inert burner</td>
</tr>
<tr>
<td>IMB</td>
<td>Intermediate main burner</td>
</tr>
<tr>
<td>LMB</td>
<td>Lower main burner</td>
</tr>
<tr>
<td>IMSAD</td>
<td>Intermediate main secondary air duct</td>
</tr>
<tr>
<td>IIB</td>
<td>Intermediate inert burner</td>
</tr>
<tr>
<td>IMSAD</td>
<td>Intermediate main secondary air duct</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>--------------</td>
<td>-----------------------------------------</td>
</tr>
<tr>
<td>NTF</td>
<td>Normalised total flow</td>
</tr>
<tr>
<td>NOF</td>
<td>Normalised O$_2$ flow</td>
</tr>
<tr>
<td>LES</td>
<td>Large eddy simulation</td>
</tr>
<tr>
<td>LTS</td>
<td>Low temperature flash</td>
</tr>
<tr>
<td>LHV</td>
<td>Lower heating value</td>
</tr>
<tr>
<td>MB</td>
<td>Main Burner</td>
</tr>
<tr>
<td>GUI</td>
<td>Graphical user interface</td>
</tr>
<tr>
<td>LIB</td>
<td>Lower inert burner</td>
</tr>
<tr>
<td>LISAD</td>
<td>Lower inert secondary air duct</td>
</tr>
<tr>
<td>LMSAD</td>
<td>Lower main secondary sit duct</td>
</tr>
<tr>
<td>LIISAD</td>
<td>Lower intermediate inert secondary air duct</td>
</tr>
<tr>
<td>LISAD</td>
<td>Lower inert secondary air duct</td>
</tr>
<tr>
<td>LMSAD</td>
<td>Lower main secondary air duct</td>
</tr>
<tr>
<td>LIISAD</td>
<td>Lower intermediate inert secondary air duct</td>
</tr>
<tr>
<td>PCDDs</td>
<td>Polychlorinated dibenzo-p-dioxins</td>
</tr>
<tr>
<td>PCDFs</td>
<td>Polychlorinated dibenzofurans</td>
</tr>
<tr>
<td>PFG</td>
<td>Product flue gas</td>
</tr>
<tr>
<td>OFA</td>
<td>Over-fire air</td>
</tr>
<tr>
<td>RANS</td>
<td>Reynolds-averaged Navier–Stokes</td>
</tr>
<tr>
<td>RFG</td>
<td>Recycled flue gas</td>
</tr>
<tr>
<td>RR</td>
<td>Recycled ratio</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>--------------------------------------------</td>
</tr>
<tr>
<td>RTE</td>
<td>Radiation transfer equation</td>
</tr>
<tr>
<td>SAD</td>
<td>Secondary air duct</td>
</tr>
<tr>
<td>SIR</td>
<td>Surface incident radiation</td>
</tr>
<tr>
<td>SIMPLE</td>
<td>Semi implicit method for pressure linked equation</td>
</tr>
<tr>
<td>UIB</td>
<td>Upper inert burner</td>
</tr>
<tr>
<td>UIISAD</td>
<td>Upper intermediate inert secondary air duct</td>
</tr>
<tr>
<td>UISAD</td>
<td>Upper inert secondary air duct</td>
</tr>
<tr>
<td>UMSAD</td>
<td>Upper main Secondary air duct</td>
</tr>
<tr>
<td>UIISAD</td>
<td>Upper intermediate inert secondary air duct</td>
</tr>
<tr>
<td>UISAD</td>
<td>Upper inert secondary air duct</td>
</tr>
<tr>
<td>UMSAD</td>
<td>Upper main Secondary air duct</td>
</tr>
<tr>
<td>VM</td>
<td>Volatile Matter</td>
</tr>
<tr>
<td>WSGGM</td>
<td>Weighted-sum-of-gray-gases model</td>
</tr>
<tr>
<td>VOF</td>
<td>Volume-of-Fluid</td>
</tr>
<tr>
<td>XRF</td>
<td>X-ray fluorescence</td>
</tr>
</tbody>
</table>
CHAPTER 1. Research Theme and Structure of the Thesis

1.1. Background of the Research

In general, much effort is currently focused on reducing greenhouse gas emissions from fuel-fired power generation. The efficiency of thermal power station has a key influence on greenhouse gas production. Improving efficiency leads to significant reduction in emissions and fuel consumption. An analysis shows that 1% improvement in power station efficiency almost delivers a 3% reduction in CO₂ emissions [1]. Based on this framework, the retrofitting and/or replacement of existing fuel-fired power plant with new-technology generation capacity can provide a better greenhouse advantage. Clean coal technologies are commonly used to define a range of technologies from high-efficiency generation systems to the ultimate, zero emission power production. As coal will remain a considerable quantity of the energy mix in the foreseeable future, so clean coal technologies allow more electricity to be produced from less coal. This will play a significant part in efficiency gains in electricity generation. Also, efficiency improvements include the most cost-effective and shortest lead time actions for reducing emissions from coal-fired power generation. This is particularly the case in developing countries where existing power plant efficiencies are generally lower and coal use in electricity generation is increasing. Improving the efficiency of pulverised coal-fired power plants has been the focus of considerable efforts by the coal industry. This increases the performance of carbon capture and storage (CCS) programs and decreases the associated economic costs. Also, efficiency gains can also be made by developing innovative ways to generate electricity from coal or reducing the amount of energy.
Besides the usage of coal in power plants, combustion technologies can be enhanced to further decrease the total costs of heat and/or power produced and to maximise safety and simplicity of operation. The need for innovation is also driven by the wish to burn new biomass fuels, such as energy crops, waste wood, and agricultural residues [2]. Co-firing biomass with coal in traditional coal-fired boilers is becoming increasingly popular, as it capitalises on the large investment and infrastructure associated with the existing fossil-fuel-based power systems while traditional pollutants (SO\(_x\), NO\(_x\), etc.) and net greenhouse gas (CO\(_2\), CH\(_4\), etc.) emissions are decreased. On the other hand, combustion in a packed bed or fixed bed has now become a recent topic of interest for biomass combustion [3, 4]. The design, operation and maintenance of such combustion equipment require detailed understanding of the burning process inside the bed. There have been many research activities into the packed bed combustion of solid fuels, mainly biomass and wastes during the last two decades [5-10]. However, the commercial application of packed bed biomass combustion system in a furnace is yet very limited due to insufficient knowledge on combustion mechanisms and processes. But, it is a very much potential system of biomass combustion which can improve the combustion efficiency, and meet more stringent government emission regulations expected in the future. It is also important to identify the amount of ash deposition on the furnace wall and the position of the deposited slag and its motion. However, it is difficult to solve these types of problems on site unobtrusively and with reasonable effort. But in order to improve the furnace efficiency and life time, determination of the amount of slag is mandatory. The answer is mathematical modelling, which leads to slag formation modelling. In recent years, a number of attempts have been made to utilize computational analysis to model the ash formation and transport process in pulverized fuel combustion system [11-20].
1.2. Different Carbon Capture Technologies

In order to understand the technologies that are used for CO₂ capture in the conventional power plants, it is important to understand the systems of leading technology for these power plants. The three main techniques, which have been developed for CO₂ capture from these different systems of leading technology, are pre-combustion capture, post-combustion capture, and capture of oxy-fuel combustion, as presented in Figure 1.1. The pre-combustion capture technique extracts CO₂ from the fuel before the burning process in the combustion chamber. The post-combustion capture technique involves capturing CO₂, as well as reducing particulate matter SOx, and NOx in the combustion flue gases. The oxy-fuel combustion technique captures carbon dioxide from the flue gases of combustion. It is similar to the post-combustion capture technique in terms of separating the CO₂ from the exhaust gases as a final process of sequestration, but it is less chemically complicated. Details about the advancements in CO₂ capture technology is described in [21]. In short, all these three CO₂ capture technologies have different outcomes, particularly with regards to reduction of power plant efficiency and in increasing the cost of electricity production. Advantages and disadvantages of different CO₂ capture approaches are illustrated in Table 1.1.

Among all the carbon capture technologies, oxy-fuel combustion is a greenhouse gases (GHG) abatement technology in which coal is burned using a mixture of O₂ and recycled flue gas (RFG), to obtain a rich stream of CO₂ ready for sequestration [22]. This carbon capture technology has been considered as one of the most effective technologies to reduce gaseous emissions. In general, the conventional boiler uses air as an oxidizer in the combustion process, hence nitrogen is the main component in the flue gas as its concentration in the air is approximately 79% by volume.
<table>
<thead>
<tr>
<th>Technique</th>
<th>Advantages</th>
<th>Barriers to implementation</th>
</tr>
</thead>
</table>
| Post-combustion [21] | This combustion technique is applicable to the majority of existing coal-fired power plants where retrofitting option is valid in terms of flue gas. Synthesis gas is normally concentrated in CO₂. High CO₂ partial pressure. More technologies available for separation. | →Flue gas is dilute in CO₂ at ambient pressure,  
→Significantly higher performance                         |
| Pre-combustion [21]  | Very high CO₂ concentration in flue gas                                      | →Applicable mainly to new plants                 |
|                      | Retrofit and repowering technology option                                    | →Required extensive support                      |
|                      |                                                                             | →Large O₂ production required                    |
|                      |                                                                             | →Decreased process efficiency                    |
But, in the oxy fuel combustion, air is replaced with oxygen and recycled flue gas mixture. The flue gas produced in oxy fuel combustion has very high concentration of CO$_2$ comparing with the flue gas achieved in the air combustion and is ready for sequestration. As CO$_2$ has higher specific heat capacity compared to N$_2$, oxy-fuel combustion flame has different radiative characteristics compared to air fired flame, so the use of oxy fuel combustion technology leads to many changes in the furnace [16, 23].

### 1.3. Co-firing and Slagging Concept

In order to meet the demand of future energy crisis and to attain sustainable development, expansion of the usage of renewable energy is important. One of the principal means of mitigating the future energy crisis is expanding the use
of renewable energy and is an approach to attain sustainable development in the world. This can be achieved by using renewable energy sources as these are CO₂ neutral. The use of biomass energy has significant contribution to the renewable energy employed today [24, 25]. Compared with other fossil fuel sources, biomass fuels contain less carbon dioxide (CO₂) [26]. Combustion is considered to be the most fundamental option of converting biomass fuels to energy. It is a very common way of burning solid fuels, relatively easy and requires less cost and is a proven technology in recent years [19, 20, 27, 28]. But, for burning uncommon fuels with, improved efficiencies and low costs, further development is necessary [27, 29-32]. The knowledge of biomass combustion and its consequent thorough process such as thermal, chemical, and mechanical techniques [24, 33-35] is still far from sufficient, though the combustion technology has a long history. Usage of biomass as a co-fired fuel has showed a significant option for the reduction of greenhouse gas (GHG) emissions. Co-firing of biomass deals with higher burning efficiency when fired with coal in power plants [25, 36]. Compared to other renewable sources, biomass always required less production cost for power generation [37-39].

Utilisation of biomass fuel with coal has become a solution for the power crisis compared to the traditional power generation options [26, 40, 41]. This is because it requires less capital investment and other available infrastructures compared to a newly developed plant. Also co-firing of biomass provides less traditional pollutants and reduces the greenhouse gas emissions. In order to apply the co-firing concepts on a large scale, selection of appropriate technologies, characterisation of proper selection of biomass, possibilities of NOₓ reduction by fuel staging, problems concerning the deactivation of catalysts, characterisation and possible utilisation of ashes from co-firing plants, as well as corrosion and ash deposition problems are important. A typical gasification systems used for indirect co-firing of coal and biomass which
Co-combustion of coal and biomass represents a sustainable, renewable energy option that promises reduction in net CO$_2$, SO$_x$ and often NO$_x$ emissions, as well as in the anaerobic release of CH$_4$, NH$_3$, H$_2$S, amides, volatile organic acids, mercaptants, esters, and other chemicals leading to several societal benefits [29, 43-46]. Knowledge about the performance of biomass combustion [37, 47, 48], its emission [42, 49-52], and firing, ashing, slagging and fouling [53-55] is still quite limited. The primary goal for researchers working in this field is to develop a possible way to convert the biomass to thermally efficient and eco-friendly energy and its subsequent mechanism.

Though coal is the main fossil fuel energy source in the world but it contains various inorganic contents such as SiO$_2$, TiO$_2$, Al$_2$O$_3$, CaO, MgO, Na$_2$O, K$_2$O, P$_2$O$_5$, Mn$_3$O$_4$, SO$_3$, Fe$_2$O$_3$ etc. During the combustion of coal in power plants,
these mineral contents are deposited as slag [53]. Slagging is a process of combustion in which the ash component is heated (at a temperature above the ash fusion temperature), becomes molten and thus deposited along the furnace refractory wall. These molten ash forms a layer called slag. Figure 1.3 shows a typical slag layer formed in a 5MW combustion test facility [56]. The deposited slag thickness is not uniform in the ceiling wall fig. 1.3 (a) and the bottom wall fig. 1.3 (b) of the furnace. This slag layer has significant effect on performance of coal based furnace. The advantage of slagging is the reduction of the disposing of unused mineral content in the environment, energy efficiency, broader fuel flexibility, and higher percentage of lower-carbon content slag residues for application [57, 58]. The deposited slag layer also works as a coating which prevents the heat loss in the gasifiers. But slagging reduces the overall efficiency of the furnace; excessive slagging reduces reliability and safety because of corrosion. For designing and optimization of the slagging combustor, it is imperative to investigate the related process occurring inside the furnace. In last decade, research has been concentrated into the effects of oxy-fuel combustion by computational fluid dynamics (CFD) [59-62]. But limited attempts are taken to investigate the slagging issue. It is very important to know the amount and location of the slag as well as its dynamics.

(a) The slag formed at the ceiling  
(b) The slag formed at the bottom wall

**Figure 1.3:** The slag formed in the 5 MWth oxy-coal combustor [56].
Fossil fuel energy is the main source of energy on the earth. Other energy sources are wind, solar, geothermal etc. Renewable energy always recognized as a supplementary source of energy and is sustainable with great potential, produces comparatively low emissions and required less production cost. That’s why it is considered as one of the main solutions to meet the demand of the energy crisis. Table 1.2 represents a worldwide renewable energy scenario for 2040. It is claimed that by the year 2040, almost half of the world’s energy will come by switching to renewable energy sources [63]. Presently, biomass is termed as one of the promising energy sources which will mitigate future greenhouse gas emissions [25, 64-67]. The primary energy consumption by energy sources and different regions are demonstrated in Table 1.3. It is seen that combustion of biomass is the most appropriate and inexpensive way to exploit biomass energy. It is accountable for over 97% of the global generation of bio-energy [68]. The use of biomass is extensive, as shown in Figure 1.4. There are a total of 62 countries in the world currently generating power from biomass resources. The United States of America is the leading biomass electricity producer at 26% of world production. Following USA, Germany (15%), Brazil and Japan (both 7%) also produce a significant amount of energy.
### Table 1.2: Scenario of world’s renewable energy set-up by 2040

<table>
<thead>
<tr>
<th>Consumption (million ton oil equivalent)</th>
<th>2001</th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomass energy source</td>
<td>1,080</td>
<td>1,313</td>
<td>1,791</td>
<td>2,483</td>
<td>3,271</td>
</tr>
<tr>
<td>Total renewable energy sources</td>
<td>1,365.5</td>
<td>1,745.5</td>
<td>2,694.4</td>
<td>4,289</td>
<td>6,351</td>
</tr>
<tr>
<td>Renewable energy contribution(% sources)</td>
<td>13.6</td>
<td>16.6</td>
<td>23.6</td>
<td>34.7</td>
<td>47.7</td>
</tr>
</tbody>
</table>

### Table 1.3: Primary energy consumption by energy sources and region [41]

<table>
<thead>
<tr>
<th>Region</th>
<th>Modern biomass</th>
<th>Traditional biomass</th>
<th>Other renewable</th>
<th>Conventional energy</th>
<th>Total primary energy</th>
<th>Modern biomass as % of primary energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>World</td>
<td>16,611</td>
<td>33,432</td>
<td>13,776</td>
<td>409,479</td>
<td>473,319</td>
<td>3.5</td>
</tr>
<tr>
<td>China</td>
<td>315</td>
<td>8,988</td>
<td>1,323</td>
<td>49,602</td>
<td>60,144</td>
<td>0.5</td>
</tr>
<tr>
<td>East Asia</td>
<td>1,092</td>
<td>3,633</td>
<td>1,197</td>
<td>20,202</td>
<td>26,145</td>
<td>4.2</td>
</tr>
<tr>
<td>Indonesia</td>
<td>126</td>
<td>1,680</td>
<td>357</td>
<td>5,418</td>
<td>7,560</td>
<td>1.7</td>
</tr>
<tr>
<td>South Asia</td>
<td>1,302</td>
<td>9,828</td>
<td>504</td>
<td>18,627</td>
<td>30,261</td>
<td>4.3</td>
</tr>
<tr>
<td>India</td>
<td>1,092</td>
<td>8,043</td>
<td>357</td>
<td>15,582</td>
<td>25,074</td>
<td>4.4</td>
</tr>
<tr>
<td>Latin America</td>
<td>2,394</td>
<td>1,239</td>
<td>2,373</td>
<td>15,834</td>
<td>21,840</td>
<td>11</td>
</tr>
<tr>
<td>Brazil</td>
<td>1,680</td>
<td>357</td>
<td>1,176</td>
<td>5,502</td>
<td>8,736</td>
<td>19.2</td>
</tr>
<tr>
<td>Middle East</td>
<td>21</td>
<td>63</td>
<td>105</td>
<td>19,341</td>
<td>19,551</td>
<td>0.1</td>
</tr>
<tr>
<td>Africa</td>
<td>2,310</td>
<td>9,702</td>
<td>315</td>
<td>12,726</td>
<td>25,074</td>
<td>9.2</td>
</tr>
</tbody>
</table>
1.5. **Need for Computational Modelling**

Experimental investigation is considered as the most appropriate method for various kind of combustion related studies. But, an experiment is not only an expensive and lengthy process but also its technically challenging and sometimes interrupts the regular operation of the plant. Though, experimental method is important but often inadequate to analyse the detailed phenomena inside the boiler, especially for industrial furnace. Lab scale analysis was another supplementary method which is extensively accepted in order to solve this type of problem. But there are some limitation in the lab scale compared to full scale analysis based on different parameters and related physics. Detailed information of different process and reaction inside the furnace, combustion phenomenon, predicting the flue gas emissions, mixing, gaseous reactions, surface combustion, and paths of particles are not possible to trace in...
experimental investigation. These limitations provide the scope to implement numerical modelling of biomass combustion.

Knowledge about the performance of coal/biomass combustion, its emission, and firing, ashing, slagging and fouling is still quite limited. Instead of performing expensive and time-consuming test runs, modelling is increasingly used to calculate flow, temperature, and residence time distributions as well as two-phase flows (flue gas and ash particles) in coal/biomass furnaces and boilers, and to evaluate the impact of design on combustion quality and emissions. Computational techniques provide the opportunity to investigate in detail, the combustion phenomena and contaminant development inside the furnace. But the success of computational analysis largely depends on the appropriate numerical technique and the physical/chemical models employed. In order to understand combustion as well as co-combustion issues and related problems associated for direct firing of biomass, modelling and analysis is must. Modelling of the biomass-pulverized coal co-firing process requires theoretical as well as numerical bases. It is essential to validate the model against experimental data. CFD modelling of biomass combustion and co-combustion with efficient turbulent model, and precise model predicting particles’ trajectories and chemical reactions on different boilers are demonstrated in the literature [67, 70-75]. Though some CFD analysis has already investigated for different types of biomass for light weight biomass, a validated and efficient numerical model is still needed for the further investigation of biomass combustion.

CFD models for coal combustion have been developed based on theoretical as well as experimental investigations [76-79], including all the stages of the combustion. Computational modelling of combustion of biomass particle is found as a major challenge due to some limitations. Though a number of
researchers and groups are working in this field, still there have been a very few number of modelling study for biomass combustion using detailed combustion models [80]. Many numerical models developed for fossil fuel combustion have been modified to apply to biomass combustion or co-combustion modelling. In addition, there are a number of available commercial CFD models and codes. Only few codes provided the features for the special effects of biomass combustion [70, 74, 81-86].

1.6. Research Gap and Challenges

From the literature it was found, that the diverse experimental studies of biomass combustion and co-combustion with coal have shown possibilities to solve different issues of the systems in pilot scale furnaces as well as full scale furnaces, and industrial furnaces [7, 45, 87-91]. Also, during the process of researches, huge amount numerical analyses were carried out [29, 73, 80, 83, 92-94]. As the availability of higher concentration of volatile material (VM) as well as lower carbon content, biomass provides lower heating value compared to other traditional fossil fuels. Combustion behaviour significantly depends on chemical content and physical structures of the fuel particles. Combustion of biomass provides some severe complications due to its characteristics that need to be concentrated properly to have a solution in order to implement for further improvement. Utilizing Biomass as a fuel increase the possibilities of slagging and fouling risk on the heat exchange surfaces, Increase of corrosion risk, decrease of boiler capacity. Besides, biomass are available in wide-ranging distributions of sizes and shapes which were considered for fuel with somewhat uniform properties. It can be mentioned that physical properties such as shape, density and irregularity, and chemical characteristics like
chemical compositions, devolatilization are the primary influencing factors during combustion.

As literature provides some inspiration, there still exist some fields which are equally important and haven’t been worked yet in details. In this work, further investigations are carried out to make some innovative and tentative study on selected areas. Though, experimental investigation is considered as the most appropriate method for such kind of study. But, an experiment is an expensive and lengthy process but also it is technically challenging and sometimes interrupts the regular operation of the plant. But often inadequate to analyze the detailed phenomena inside the boiler, especially for industrial furnace. Lab scale analysis is widely accepted way to solve this type of problem. But still there are some limitation in the lab scale compared to full scale analysis based on different parameters and related physics. Detailed information of different process and reaction inside the furnace, combustion phenomenon, predicting the flue gas emissions, mixing, gaseous reactions, surface combustion, and paths of particles are not possible to trace in experimental investigation. These limitations provide the scope to link the gap using numerical modelling of biomass combustion.

It is essential to model the combustion phenomena in order to discover potential problems that may occur during biomass firing and co-firing and to mitigate potential negative effects of biomass fuels, including lower efficiency due to lower burnout. A detail CFD study is required to scrutinize the co-firing of coal and larger having irregular shaped biomass particles burnout is vital. To better understand the biomass combustion and thus improve the design for co-firing biomass in wall-fired burners, non-sphericity of biomass particles is also important. Non-sphericity of biomass particles in order to model biomass combustion accurately is a challenging task in CFD which requires further
analysis. Combustion of different sizes of biomass particles will be interesting. One of the determinations of this study is to study combustion behaviour of the biomass components in the blend of coal and biomass using CFD modelling. An optimum co-firing ratio in which the biomass provided heat input is also interesting to investigate. Commercial CFD models often ignore thermal gradients within the particles and this leads to inaccuracy. In this study, a combustion model for the heat transfer of large irregular shaped particles is developed. The effects of particle distribution on the combustion characteristics in terms of ignition, devolatilization and char combustion for co-firing case of an industrial combustion test facility.

Slagging and fouling is also an interesting phenomenon that can be explored in details. One of the main objectives of this study is to explore the fundamentals of slag flow modeling and to analyze the present scenario of modelling coal combustion technology, tools developed for the prediction of slagging behavior of the fuel ash in combustion applications. Overall, this research work provides an extensive investigation of the fundamental aspects and emerging trends in developing numerical model of slag formation and co-firing of different types of biomass fuel in industrial furnace.

1.7. Scopes and Objectives

*Ignition, devolatilization, char burnout performance of coal combustion*

The first objective of the research is to develop a comprehensive model for simulating the combustion of coal under different conditions. This Computational modelling is carried out in order to calibrate and validate model with the data of existing test facilities of a drop tube furnace for coal combustion using wide range of particle diameter. This Computational study
will be helpful for future development of co-firing of biomass. In this numerical modelling of radiative and convective heat transfer performance of oxy-fuel combustion which is very important for designing a new or retrofit an existing boiler with oxy fuel combustion capability considering two major form of heat transfer. The detailed objective of this task is to identify and analyse the ignition, devolatilization, and char burnout phenomena for Russian coal combustion in a furnace in air and recycled flue gas (RFG) enriched environment and the overall combustion performance for direct coal combustion of particle.

Validation of biomass co-firing model in a small scale test facility

Co-firing biomass with coal in existing power plants offers a relatively inexpensive and efficient option. So, the use of fossil fuels with biomass can be a possible way of CO\textsubscript{2} reduction technique. Up to present, biomass has not been included extensively in a large scale power plant. Literature shows that, still more knowledge and investigation is required to use biomass as a co-fired fuel with fossil fuel in order to provide the fuel supply. Coal combustion can be shared with biomass co-utilization in small percentage. Co-firing can be achieved by various ways, as for example direct, indirect, biomass gasification and then firing of the gas in the furnace. A model is developed for co-firing biomass with coal which will be simulated in a lab scale furnace to determine the radiative and convective heat transfer performance of oxy-fuel combustion.

Performance of straw combustion for below zero emissions in a reactor

Due to irregularities of the size and shape of the biomass particle, development of the co-firing model for long irregular shaped particles and their heating profile are important. Few experimental investigations have been conducted using straw as a co-fired fuel under air and oxy-fuel environments. It is anticipated that advance effort on co-firing of biomass (like straw) and coal in
oxy-fuel environment will expose comparable changes to the burning characteristics. However, this area of research is still relatively young when considering suspension-fired boilers and research on oxy-fuel combustion of pulverized biomass. The objective of this study is to improve the fundamental knowledge on straw combustion in a swirl stabilized furnace by clarifying the effect of the change in combustion atmosphere on fuel burnout: flame temperatures, emissions of polluting species when pure straw and blends of coal and biomass are combusted in air and oxy-fuel atmospheres.

**Application of co-firing model in a dedicated large scale coal-fired furnace**

Up to present, biomass has not been included extensively in a large scale power plant in Victoria, Australia. As oxy-fuel combustion is suggested as one of the possible and promising technologies for capturing CO\(_2\) from power plants, hence, a detailed analysis is introduced for co-firing of biomass in a dedicated coal-fired furnace located in Victoria, Australia. The key objectives of this study are: i) to establish the consequence of reequipping of existing power plant for O\(_2\)/CO\(_2\) biomass co-fired combustion. ii) to explore the behaviour of the furnace such as heat transfer, calculation of carbon in Ash and the effect of biomass co-combustion for numerical models. iii) to identify optimal solution for oxy-fuel condition in existing furnace. iv) to develop and modify the existing model ready for use in industrial application.

**Model development for predicting slagging behaviour in combustor**

The development of slag formation mechanism including particle capturing model, slag flow model, wall burning model are important for the investigation of the coal-water slurry type fuel combustion. This objective of this study is to develop a comprehensive model for determining the impact and adhesion of particle on the surface of the wall during spraying to provide information of the nature of particle hitting at the furnace wall. The aim of the study is to validate
the developed model by tracing the slag deposited due to particle-wall interaction on the furnace wall. Simulation of particle deposition in a lab scale test facility for coal combustion under oxy-fuel combustion will help to incorporate this model with further development and to predict the slagging phenomenon in full scale furnace. The final goal of this modelling is to apply this model in a dedicated coal-fired furnace under oxy-fuel concept. The movement of the particles, wall/particle interaction, particle capturing criteria, flow of the deposited slag, and wall burning characteristics is explored in details. This will allow a more precise estimation of the movements of particle and their combustion behaviours for real life furnaces.

1.8. Numerical Methodology

It is important to be able to accurately calculate and predict the temperature levels, turbulent flow fields, species concentrations, burnout efficiency and emission levels from combustion equipment, especially with the present concerns about greenhouse gas (GHG) emissions. In this research, a details investigation of by three dimensional (3D) computational fluid dynamics (CFD) simulation of coal/biomass combustion and slag formation characteristics under different operating conditions (air/oxy-fuel) are carried out by a commercial CFD code, AVL Fire (version.2009.2 and version.2014) to analyse the computational domain system that includes chemical reaction mechanisms (single step and multi-step), convective and radiative heat transfer performance, fluid flow field, effects of turbulent models, char capturing model, entrainment model, splashing model, wall burning model etc. In this numerical simulation, an Eulerian-Lagrangian (gas phase-particulate phase) approach is employed for two-phase fluid flow. In order to solve the chemical reactions such as devolatilization and char burnout, char capturing and wall burning
process for coal-water slurry combustion modelling, drag effects of the irregular shaped biomass particles, appropriate subroutines were written and coupled with the code. As combustion consists of complex carbon-oxygen reactions, devolatilization and char oxidation are expressed in the form of homogeneous and heterogeneous reactions. The suitability of different chemical reactions are demonstrated in [95] for coal combustion. Char oxidation is mainly governed by the diffusion of $O_2$. For char combustion modelling, several reaction mechanisms (Global power law) are suggested in literature [95-97]. The limitations of the global power law is its dependence on temperature and oxygen partial pressure to the order of char reaction rate and CO/ CO$_2$ production rate as described by Hurt and Calo [98]. In the recent studies [62, 95, 96, 99, 100], the burning of coal particles or its consumption was assumed as the combined hydrocarbon volatile gas burning and char residual oxidation. As there was no critical differences between methane and product from devolatilization of coal used, all the hydrocarbon (HC) gas was considered as methane equivalent as suggested by [79]. To illustrate the applications of combustion modelling in CFD, it is important to define all the mathematical models that relate to the combustion phenomenon. The principle processes involved in the combustion model illustrated in Figure 1.5. The details of each model, related sub-models and their application and suitability for the specific cases were explained in details in the related chapters.
1.9. Structure of the Thesis

The present research work includes some possible technologies for the reduction of CO\textsubscript{2} from pulverized coal fired power plants keeping high efficiencies and other low emissions by using a wide variety of fuel like biomass using CFD method. The purpose is to increase the knowledge of the physical processes occurring inside the furnace and to be able to model them in a precise way. A complete model relating to combustion includes coal/biomass combustion; co-firing, oxy-fuel combustion, in laboratory/industrial scale furnaces is developed in this work. Investigations of the overall furnace and combustion behaviour, investigation of slagging and fouling behaviour will also be considered. The overall objective of this research is to determine the most favourable optimized combustion model considering radiative and convective heat transfer for retrofitting purpose, optimum co-firing ratios of biomass combustion under oxy-fuel conditions and to develop a comprehensive
model to predict the slagging characteristics inside the furnace walls. In order to attain this goal, this thesis focuses on the following steps:

In chapter two (02), different experimental and numerical studies performed are reviewed, grouped and summarized based on the fuel processing technology, burnout performance, emission level, environmental aspect, ash information and deposit characteristics, effect of co-firing ratios and adoption of oxy-fuel co-firing. Overall, this comprehensive literature review will highlight the existing technologies and emerging trends in co-firing of different types of biomass which is helpful for future investigations. It is suggested that co-firing coal with biomass has a substantial effect on SOx and NOx emission level. The ashing process, fly ash quality depends on the conversion technology, capture technology and the properties of the biomass. In order to control the furnace efficiency and production, burnout, optimum injection of biomass sharing with specific information of particle ignition properties are also important. In order to solve the detailed information of different processes and reactions inside the furnace, combustion phenomenon, predicting the flue gas emissions, proper mixing of the fuels, chemical reactions, particles combustion, and the trajectories of particles are not possible to track in experimental investigation. These limitations provide the scope to implement numerical modelling of biomass co-firing and slag formation modelling.

In chapter three (03), a numerical investigation on the radiative and convective heat transfer performance of the combustion of pulverized Russian coal in a 0.5MWth combustion test facility (CTF) has been conducted for air and CO2-rich oxy-fired environment. Different combustion environments were investigated including an air-fired as reference case and three recycled flue gas (RFG) fired combustion environments. It was found that the flame temperature distribution for the air fired and RR72% case were found to be similar. The flame
temperature increased with O$_2$ concentration and decreasing RR. With the
decrease of RR, the length of the flame is also shortened. The ignition condition
improved with enriched O$_2$ concentration in the RR65% case. The presented
working range for the Russian coal, suggests that the air equivalent radiative
heat flux can be obtained at a RR of ≈71% while air equivalent flame
temperature were observed at RR of 72%.

In chapter four (04), a computational fluid dynamics (CFD) model has been
developed for the co-firing of pulverized Russian coal with biomass (called
Shea meal) having different blending ratio in a 0.5MWth combustion test
facility for air and CO$_2$-rich environment. User defined subroutines for the
aerodynamics of irregular shaped biomass particle; devolatilization and char
Combustion modelling are used. The relationship of the peak and mean flame
temperature and furnace exit temperature with the normalized total flow and
normalized O$_2$ are presented. The working range for the co-firing of 20%
biomass sharing suggested that optimum recycled ratio (RR) for flame
temperature and radiative heat transfer to be closely matched with air-firing
found at 71%, but for 40% sharing, a value of RR70% may be needed. This study
highlights the possible effects of varying the fuel on ignition environment and
heat transfer characteristics of a small scale furnace, emphasizing the minor
reform that may be needed when transforming to higher biomass sharing co-
firing.

In chapter five (05), the combustion behaviour of long irregular shaped biomass
like straw in air and O$_2$/CO$_2$ mixtures has been predicted for air-fuel and oxy-
fuel (25%, 30% and 35% O$_2$) cases were considered maintaining a constant
thermal load of 30 kW in a semi-technical scale once-through swirl-stabilized
furnace. The impact on the burning characteristics including flame temperature,
burnout, and emissions for pure coal to pure straw combusted in air/oxy-fuel
atmosphere were evaluated. It was found that with 20% straw sharing, sensible performances were observed similar to that of 100% coal combustion. The CO levels are predicted to decrease in the oxy-fuel combustion compared to air-firing flames due to O₂ availability. Also a critical analytical analysis was conducted to investigate the heating performance for straw particle of different sizes. The heating profiles show significant differences between the three particle sizes assuming isothermal temperature gradient and heating by both radiation and convection.

In chapter six (06), the co-firing model has been applied in a dedicated 550MWth tangentially coal-fired furnace. Three different co-firing cases (20% biomass with 80% coal, 40% biomass with 60% coal and 60% biomass with 40% coal) were considered under air-firing and three different oxy-firing cases (25% O₂/75% CO₂, 27% O₂/73% CO₂ and 29% O₂/71% CO₂). Results were presented by the aerodynamics of burner flow, temperature distributions, gaseous emissions such as O₂ and CO₂ distributions etc. With the increase of biomass sharing, peak flame temperature reduced significantly. Comparatively, improved burnout is observed for the improved oxy-fuel cases. On the other hand, CFD model predicted a significant increase in unburned carbon in fly ash for the increase of biomass co-firing sharing. Overall, this study highlights the possible impact of changing the fuel ratio and combustion atmosphere on the boiler performance, underlining that minor redesign may be necessary when converting to biomass co-firing under air and oxy-fuel conditions.

In chapter seven (07), the development of three dimensional (3D) slagging combustion model for coal-firing in a tangentially-fired furnace under different combustion conditions were presented. The overall objective of this study was to explore the fundamentals of slag flow, particle capturing criteria, burning characteristics of the deposited particles on the furnace wall using CFD package
coupled with some user-defined code. In order to describe the slagging combustion, Eulerian-Lagrangian model of the gas-particle flow was coupled with the slag flow, char capturing and wall burning sub-model. This study was performed considering two cases. Initially, validation of the model was achieved by comparing the available experimental and numerical data for coal-water slurry combustion in 3MWth small scale furnace. The slag thickness deposited on the furnace wall was found to be reasonably in good agreement with the available data. Visualization of the slag flow and the combustion related emissions are presented. Later, validated slag model was applied in a 550MWth coal-fired furnace for determining the effects of slagging behaviour of the Brown coal combustion under oxy-fuel condition. Results are presented in terms of slag thickness, slag velocity on different walls under oxy-fuel condition. Also the effects of species mass fraction, flame temperature and flow distribution in different plane of the furnace were presented. Overall, this study will provide a guideline for predicting slag formation in industrial furnace.
CHAPTER 2. Literature Review and Scope of Research

2.1. Status of Coal Combustion Technology

Combustion of fossil fuel is a proven thermo-chemical conversion technology for heat and power production which is connected with formation of pollutant, also a source of deterioration of the global environment. Coal is a major source of fossil fuel, responsible for generating electrical energy in the world [101]. Also, combustion of coal results in the emission of greenhouse gases, the accumulation of which in the atmosphere since the start of the industrial revolution has been contributing to climate change [102]. In this concern, international efforts, like Kyoto protocol bound an obligation for the reduction of emissions specially CO$_2$ from industrialized countries. For the reduction of CO$_2$ emissions from coal fired power plants, a number of CO$_2$ capture technologies, can be implemented for continuing the use of fossil fuel [21, 102-105] such as post-combustion capture, pre-combustion capture, and oxy-combustion. Apart from these processes, different separation techniques are also suggested as gas phase separation, absorption, adsorption and hybrid processes.

Recent developments in the CO$_2$ capture technologies include some innovative concepts (i.e. calcium looping, chemical looping, and amines scrubbing systems) suggested in literature. Calcium looping (CaL), a post combustion capture technology, is suggested as a competitive concept for CO$_2$ reduction technique [106] for power plants. CaL is achieved by oxy-firing for the generation of CO$_2$ rich flue gas which is absorbed by CaO and CaCO$_3$ in carbonator. But this technique is relatively more energy consuming. The ECO-Scrub combustion concept [16], a combination of partial oxy-fuel combustion
and post combustion capture, provide comparatively higher efficiency than only post combustion process. Another important concept is chemical looping combustion (CLC) [77, 107-110]. In CLC, high purity and concentrated CO₂ stream is produced as there is no contact between the fuel and the air as metal oxide works as transportation media for O₂. Hence, lower energy is required compared to other CO₂ separation processes.

In recent years, many efforts have been devoted to the development of oxy-fuel technology [18, 23, 102, 111-116]. From pilot-scale and laboratory scale experimental studies, oxy-fuel combustion has been found to differ from air combustion in several ways, including reduced flame temperature, delayed flame ignition and reduced greenhouse gas (GHG) emissions [102]. Several small scale experimental studies have been conducted [18, 19, 116-125] at various combustor design.

A 20 KW down-fired coal combustor was considered by Liu et al. [117] using the coal in air and in oxy coal environment. Significant differences were observed in the char burnouts and gas temperatures in oxy fuel combustion case. Another study considering an entrained flow reactor was used in [126] to investigate experimentally the ignition and burnout of coals under oxy-fuel conditions. The ignition temperature of the individual coals showed a strong dependence on the composition of the atmosphere. The burnouts of the samples with a mixture of 79% CO₂-21% O₂ are lower than those conducted in air. When the O₂ in the mixtures is improved to a value of 30%, the burnout is higher than in air. Suda et al.[119] conducted the experimental study in a chamber considering different kinds of coal particles to investigate the effect of carbon dioxide (CO₂). Another experimental study for the firing of dry lignite under O₂ enriched environment in a 0.5MW test facility has been conducted by Kass et
al. [121] focusing on the flue gas compositions in air and oxy-fuel combustion condition.

Several numerical attempts have been made to computationally model the combustion in oxy fuel environments in recent years [125, 127-129]. Edge [129], in his numerical study, investigated the effect of radiation to the furnace wall by using large eddy simulation (LES) and Reynolds-averaged Navier–Stokes (RANS) based governing equations. The flame properties were clarified for coal combustion in an air- and oxy-fired combustion test facility (CTF).

Recently, Audai et al. [62, 95, 96, 99, 100] carried out comprehensive modelling for the combustion of pulverized dry lignite in lab scale [95, 96, 99] and large scale [62, 100, 130, 131] furnaces under different combustion environments. The studies demonstrated the flame ignition changes and the ignition stability of coal flame in air and oxy fuel combustion scenarios. The effects of SOx and NOx emission concentration have also been investigated. These numerical results showed that the flame temperature distributions and O₂ consumptions in the oxy fuel case were approximately similar to the air combustion case for 25% O₂ and 75% RFG.
### Table 2.1: Summary of selected full-scale technology evaluations

<table>
<thead>
<tr>
<th>Combustion application</th>
<th>Focus of study</th>
<th>System features/Techno-economic performance</th>
<th>Refs.</th>
</tr>
</thead>
</table>
| 1000 MW pulverised coal-fired power plant | Evaluating the thermal efficiency and economy of a CO₂ recovery power plant burning characteristics of pulverised coal in O₂/CO₂ conditions | → Oxygen generation: a cryogenic ASU with an optimum oxygen purity of 97.5%  
→ Recycle system: wet recycling used with the recycling position after pollutant controls  
→ Flue gas treatment: a filter for further gas clean, a gas pre-cooler, and a compressor  
→ CO₂ recovery and sequestration: 90%, direct underground disposal | [132] |
| Pulverised coal fired boilers (30 MW, 100 MW, 200 MW, 500 MW) | Comparing the capital and operating costs of oxygen-fired pulverised coal boilers for pollutant controls to the costs of conventional air-fired boilers | → Recycle system: flue gas recycled before pollutant controls  
→ Pollutant controls: no DeNOₓ, Hg removal, FGD  
→ Flue gas treatment: not included  
→ CO₂ recovery and sequestration: not analysed | [133, 134] |
<table>
<thead>
<tr>
<th>Plant Type</th>
<th>Description</th>
<th>Process Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>VEAG 2x933 MW lignite-fired power plant</td>
<td>Evaluating the overall process of an O₂/CO₂ power plant to find options for energy optimisation</td>
<td>→ Oxygen generation: a cryogenic ASU with a oxygen purity of 95% → Flue gas recycled from the boiler between economiser and air heater → Pollutant controls: no DeSOₓ → Flue gas treatment: a condenser, compressors, a gas hydration unit, non-condensable gas removal unit</td>
</tr>
<tr>
<td>AEP’s 450 MW Conesville Unit 5</td>
<td>Evaluating the technical performance of alternate CO₂-capture and sequestration technologies for an existing coal-fired power plant</td>
<td>→ Oxygen generation: a cryogenic ASU with a oxygen purity of 99% → Recycle system: about 2/3 flue gas → Flue gas treatment: a gas cooler, a CO₂ compression and liquefaction system → CO₂ recovery and sequestration: 94% of CO₂ recovery and 97.8% CO₂</td>
</tr>
</tbody>
</table>

→ Using ASPEN Plus model for developing a system, to characterise mass and energy flows in the system → Evaluating the fate of sulphur in the gas path and the performance of sulphur removal → Cryogenic ASU with an O₂ purity of 99% → Wet recycle system → Flue gas treatment: a gas dryer, non-condensable gas removal system, a CO₂ compression system |
<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 400 MW pulverised Coal fired power plant</td>
<td>Assessing the techno-economic performance of CO₂ capture from an existing power plant with MEA scrubbing and O₂/CO₂ recycle combustion</td>
<td>→ Oxygen generation: a cryogenic ASU with a oxygen purity of 99.5% Dry gas recycling → a compressor and a low temperature flash (LTF) unit to capture CO₂ in flue gas → CO₂ concentration is 98% [141, 142]</td>
</tr>
<tr>
<td>600 MW power plants</td>
<td>Assessing the performance of various combinations of power generation, CO₂ capture and sequestration technologies for fossil power plants</td>
<td>→ Power generation: LNG C/C, Oxy-fuel USC pf, O₂-blown IGCC, air-blown IGCC, → CO₂ capture: O₂/CO₂ combustion, chemical absorptions MEA or MDEA and physical absorptions SELEXOL or PSA NGCC, Direct fired coal CC, IGCC, wind. [143]</td>
</tr>
<tr>
<td>New ‘Greenfield’ sites and three retrofits</td>
<td>Assessing the most economic CO₂ capture technology</td>
<td>→ Amine scrubbing vs oxy-fuel combustion under future air emission restrictions → Air-firing should be possible for the oxy-fuel plant [145, 146]</td>
</tr>
<tr>
<td>Fuel type</td>
<td>Proximate analysis</td>
<td>Ultimate analysis</td>
</tr>
<tr>
<td>------------------</td>
<td>--------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td></td>
<td>Moisture</td>
<td>Ash</td>
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<tr>
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<tr>
<td>Corn cobs</td>
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<td>Barley straw</td>
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<tr>
<td>Wheat straw</td>
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</table>

(a). Biomass fuels
### (b). Wood products

<table>
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<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
<th>K</th>
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<td>-</td>
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<td>70</td>
<td>18</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>16,100</td>
<td>-</td>
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<td>76.2</td>
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<td>46.9</td>
<td>5.2</td>
<td>37.8</td>
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<td>0.0</td>
<td>18,140</td>
<td>5.55</td>
<td>2279</td>
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<td>72.6</td>
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<td>Hardwood</td>
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[153] [154] [155] [156] [32] [82]
### (c). Food processing residue

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<td>44.98</td>
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<td>42.27</td>
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<td>19900</td>
<td>-</td>
<td>-          [158]</td>
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<td>Walnut shells</td>
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<td>-</td>
<td>19.85</td>
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<td>39.14</td>
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<td>0.05</td>
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</table>

### (d). Energy crops

<table>
<thead>
<tr>
<th>Material</th>
<th>-</th>
<th>1.33</th>
<th>-</th>
<th>16.35</th>
<th>48.45</th>
<th>5.85</th>
<th>43.69</th>
<th>0.47</th>
<th>0.01</th>
<th>19380</th>
<th>5.7</th>
<th>2347 [152]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poplar</td>
<td>-</td>
<td>0.52</td>
<td>-</td>
<td>16.93</td>
<td>48.33</td>
<td>5.89</td>
<td>45.13</td>
<td>0.15</td>
<td>0.01</td>
<td>19350</td>
<td>5.6</td>
<td>2388 [152]</td>
</tr>
<tr>
<td>Eucalyptus</td>
<td>-</td>
<td>5.2</td>
<td>71.7</td>
<td>15.1</td>
<td>47.7</td>
<td>6.0</td>
<td>44.4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-          [30]</td>
</tr>
<tr>
<td>Wheat straw</td>
<td>8.0</td>
<td>5.45</td>
<td>69.57</td>
<td>16.56</td>
<td>42.81</td>
<td>5.34</td>
<td>0.50</td>
<td>0.08</td>
<td>-</td>
<td>24930</td>
<td>-</td>
<td>-          [82]</td>
</tr>
<tr>
<td>Miscanthus</td>
<td>8.42</td>
<td>6.2</td>
<td>45</td>
<td>6.2</td>
<td>52</td>
<td>8</td>
<td>32.3</td>
<td>6</td>
<td>1.2</td>
<td>-</td>
<td>-</td>
<td>-          [161]</td>
</tr>
</tbody>
</table>

### (e). Municipal residue

<table>
<thead>
<tr>
<th>Material</th>
<th>16-18</th>
<th>11-20</th>
<th>67-78</th>
<th>6-12</th>
<th>-</th>
<th>-</th>
<th>-</th>
<th>-</th>
<th>-</th>
<th>15950</th>
<th>-</th>
<th>- [159]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSW</td>
<td>0.5</td>
<td>6.1</td>
<td>65.2</td>
<td>28.7</td>
<td>81.5</td>
<td>7.1</td>
<td>3.4</td>
<td>0.5</td>
<td>1.4</td>
<td>36800</td>
<td>11.66</td>
<td>2492 [160]</td>
</tr>
<tr>
<td>Tires</td>
<td>5.5</td>
<td>43</td>
<td>45</td>
<td>6.2</td>
<td>52</td>
<td>8</td>
<td>32.3</td>
<td>6</td>
<td>1.2</td>
<td>-</td>
<td>-</td>
<td>-      [161]</td>
</tr>
<tr>
<td>Sewage sludge</td>
<td>4.4</td>
<td>27.2</td>
<td>60.9</td>
<td>7.5</td>
<td>43.8</td>
<td>7.2</td>
<td>18.2</td>
<td>.9</td>
<td>.2</td>
<td>-</td>
<td>-</td>
<td>-      [161]</td>
</tr>
</tbody>
</table>
2.2. Fuel Characterisation and Properties

There are many varieties of biomass fuels available in the environment ranging from woody to grassy and straw-derived materials. There is a significant variation in properties of biomass fuel compared to coal properties. Generally, biomass fuels are classified depending on their origin and properties. Based on the origin, these can be classified into four types such as primary residues, secondary residues, tertiary residues and energy crops. Primary residues include biomass such as wood, straw, cereals, maize, etc. these are generally obtained from the by-products of forest products and food crops. Secondary residues include saw and paper mills, food and beverage industries, apricot seed, etc. Secondary residues are derived from processing biomass material for industrial and food production. Tertiary residues include waste and demolition wood, etc. These are derived from other used biomass materials [67, 162]. Also, biomass can be classified based on the properties. These include woody biomass; herbaceous biomass; wastes and derivate; and aquatic biomass (kelp, etc.) [48, 163, 164]. The energy crops include Willow, Poplar, Cottonwood, Switch grass, Red canary grass, Miscanthus, etc. The detailed classification of biomass fuels are presented in Figure 2.1 based on Ref. [165].

In biomass, comparatively higher ash contents are observed (1% to over 20%) and less nitrogen is available (varies from around 0.1% to over 1%). The moisture content in biomass fuel is always high compared to coal, and higher chlorine content is also found. But the biomass fuels possess lower heating value having low bulk density. These properties affect the design, operation, and performance of co-firing systems. Table 2.2 summarizes the chemical analysis and properties of selected biomass fuels used for various co-firing studies.
The negative side of the biomass combustion is found during incomplete combustion due to wet or high density biomass particles resulting in carbon burnout. The amount of unburned carbon is not significant as there are low amount of carbon in biomass due to small fraction of biomass fuel co-fired. Compared to others properties, high chlorine or high-alkali biomass fuels such as herbaceous crops are responsible for high temperature corrosion of the superheater. Normally high–alkalis containing biomass fuel settled down on the heat transfer surfaces and amplify Cl concentration to the highest degree. However, there is a solution to reduce the alkali chlorides (primarily from the biomass) while reacting with the sulphur (primarily from the coal) to form alkali sulphates. But this problem is not as serious compared to the benefits of its applications.

Pyrolysis of the fuel helps in calculating the level of various components. By definition, pyrolysis is the fundamental principle underlying carbonization and proximate analysis. Pyrolysis of coal occurs in all coal conversion processes and is perhaps the most difficult to model mathematically. A number of models on coal pyrolysis have been proposed during the past several decades. However, very few of these models address the simultaneous changes in product distribution and particle weight loss (or conversion) over a wide range of operating conditions. The mechanism of pyrolysis proposed by several authors [166-168] are presented in Figure 2.2.
Figure 2.1: Major solid biomass materials of industrial interest on a global scale (adapted from [165])
Figure 2.2: The mechanism of cellulose pyrolysis proposed by several authors. (a). Bradbury et al. [166], (b). Piskorz et al. [167] and (c). Banyasz et al. [168].
<table>
<thead>
<tr>
<th>Fuel types and properties</th>
<th>System description</th>
<th>Descriptions and outcomes</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal/wood chips blends.</td>
<td>Grate-fired boiler</td>
<td>Wood includes birch, aspen, spruce etc. Coal/wood blend contains 35–41% moisture. Only 10–20% of wood co-firing is possible. It is difficult to mix the blend.</td>
<td>[169]</td>
</tr>
<tr>
<td>Coal: 22605 (kJ/kg)</td>
<td>burner</td>
<td></td>
<td></td>
</tr>
<tr>
<td>wood: 17742 (kJ/kg)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coal/manure blends.</td>
<td>35.4 kW Down-fired</td>
<td>Ignition is found easy with blend of coal/manure, 20% manure (mass basis). The feed rate of the blend was 100 g/min. The level of SO\textsubscript{x} and NO\textsubscript{x} decrease with blend combustion.</td>
<td>[170]</td>
</tr>
<tr>
<td>Coal: 26535 (kJ/kg)</td>
<td>concentric swirl</td>
<td></td>
<td></td>
</tr>
<tr>
<td>manure: 8650 (kJ/kg)</td>
<td>burner</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coal/sawdust blends.</td>
<td>500 kW Wall-fired</td>
<td>Secondary swirl of 1.0 is considered. The size of fuel particles were, Coal: 74% &lt;90 \mu m, sawdust: 75% &lt;1.4 mm. Higher burnout 81–90% was observed. NO\textsubscript{x} level significantly reduced. Optimum co-firing ratio of 30% is suggested for maximum burnout with minimum NO\textsubscript{x}.</td>
<td>[171]</td>
</tr>
<tr>
<td>Coal: 32260 (kJ/kg)</td>
<td>dual fuel burner</td>
<td></td>
<td></td>
</tr>
<tr>
<td>sawdust: 18140 (kJ/kg)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coal/straw/woodchips blends.</td>
<td>20 MW Multi-circulating fluidized bed combustor</td>
<td>Fuels are introduced through separate inlets. Coal/wood injected at bottom while straw injected with secondary air. The amount of biomass sharing is 18–49%.</td>
<td>[172]</td>
</tr>
<tr>
<td>Coal/straw/woodchips blends.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coal/manure blends</td>
<td>15.2 cm (dia)×1.57 m</td>
<td>A three-mixture fraction approach was introduced here. The comparisons of two- and three-mixture fraction approaches were presented. Higher burnout with blend, differences in the near burner region of temperature and species concentration</td>
<td>[173]</td>
</tr>
<tr>
<td>Coal: 26535 (kJ/kg)</td>
<td>(height) swirl</td>
<td></td>
<td></td>
</tr>
<tr>
<td>manure: 8650 (kJ/kg)</td>
<td>combustor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel Type</td>
<td>Technology</td>
<td>Mass Basis</td>
<td>Comments</td>
</tr>
<tr>
<td>---------------------------------</td>
<td>------------------</td>
<td>--------------------------</td>
<td>--------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Coal: 25500 (kJ/kg)</td>
<td>50 MW Wall-fired</td>
<td>The coal/switch grass was co-fired at 15% mass basis. A higher amount of moisture content is observed (12% moisture in biomass).</td>
<td></td>
</tr>
<tr>
<td>switch grass: 15997 (kJ/kg)</td>
<td>boiler</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coal/straw/cereal blends.</td>
<td>500 kW Wall-fired</td>
<td>0–100% biomass firing heat basis.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>boiler</td>
<td>Three different burner configurations studied</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fuel with higher nitrogen content should be injected in fuel rich zone to reduce NO(_x). Optimum co-firing ratio=60%</td>
<td></td>
</tr>
<tr>
<td>Coal/railroad ties.</td>
<td>Spreader-stoker</td>
<td>0.5–1 Mbtu/h 20% co-firing mass basis</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>NO(_x) reduced by 25% due to low nitrogen content of biomass. CO reduced considerably at low excess air ratios</td>
<td></td>
</tr>
<tr>
<td>Coal/hard wood/soft wood blends.</td>
<td>38 kW Down-fired</td>
<td>15% co-firing mass basis, 12% moisture in biomass, Both co-firing and re-burning tests were conducted.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PC furnace</td>
<td>Co-firing: unstaged combustion, NO(_x) decreased by about 17% at 50NO(_x) reduction achieved in reburn. optimal stoichiometry for reburn=0.85</td>
<td></td>
</tr>
<tr>
<td>Coal/straw/sewage</td>
<td>Down-fired</td>
<td>0.5 MW 20% co-firing of straw (mass basis), 11% moisture in straw Max. Particle size for complete burnout: 6 mm for straw. Burner configuration important in NO(_x) reduction</td>
<td></td>
</tr>
<tr>
<td>Coal: 30,140 (kJ/kg)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>straw: 17,090 (kJ/kg)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>sewage: 10,510 (kJ/kg)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 2.4: Co-firing tests performed at pilot scale, laboratory and full-scale utility boilers.

<table>
<thead>
<tr>
<th>No.</th>
<th>Fuel type</th>
<th>Furnace type</th>
<th>Scale</th>
<th>Organizations/Researchers</th>
<th>Refs.</th>
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<tbody>
<tr>
<td>1</td>
<td>co-firing sander dust with coal</td>
<td>cyclone boiler</td>
<td>Full scale</td>
<td>Northern States Power</td>
<td>[176]</td>
</tr>
<tr>
<td>2</td>
<td>lignite–biomass–waste blends</td>
<td>pilot scale incinerator</td>
<td>Pilot scale</td>
<td>Skodras</td>
<td>[177]</td>
</tr>
<tr>
<td>3</td>
<td>Co-firing forest debris</td>
<td>pulverized coal boiler</td>
<td>Full scale</td>
<td>Santee Cooper Electric Coop.</td>
<td>[176]</td>
</tr>
<tr>
<td>4</td>
<td>municipal solid waste (MSW)</td>
<td>bubbling fluidized bed</td>
<td>Lab scale</td>
<td>Suksankraisorn</td>
<td>[178]</td>
</tr>
<tr>
<td>5</td>
<td>Commercial coal/biomass</td>
<td>fluidized-bed combustor</td>
<td>Full scale</td>
<td>Tacoma Public Utilities</td>
<td>[176]</td>
</tr>
<tr>
<td>6</td>
<td>sewage sludge</td>
<td>300 kW test facility</td>
<td>Lab scale</td>
<td>Wolski</td>
<td>[179]</td>
</tr>
<tr>
<td>7</td>
<td>Waste wood co-firing tests</td>
<td>pulverized coal boiler</td>
<td>Full scale</td>
<td>Georgia Power &amp; South Company Ser.</td>
<td>[176]</td>
</tr>
<tr>
<td>8</td>
<td>sugar-cane bagasse</td>
<td>two-stage laboratory furnace</td>
<td>Lab scale</td>
<td>--</td>
<td>[180]</td>
</tr>
<tr>
<td>9</td>
<td>Tire-derived fuel co-firing test</td>
<td>wall-fired grate-equipped boiler</td>
<td>Full scale</td>
<td>Iowa State University</td>
<td>[176]</td>
</tr>
<tr>
<td>10</td>
<td>rice husk with bituminous coal</td>
<td>120 kWth FB combustor</td>
<td>Lab scale</td>
<td>Madhiyanon</td>
<td>[181]</td>
</tr>
<tr>
<td>11</td>
<td>low percentage of wood</td>
<td>wall-fired PC boiler</td>
<td>Full scale</td>
<td>TVA</td>
<td>[176]</td>
</tr>
<tr>
<td>12</td>
<td>biomass-coal blends</td>
<td>quartz dual-bed reactor</td>
<td>Lab scale</td>
<td></td>
<td>[182]</td>
</tr>
<tr>
<td>13</td>
<td>low percentage of wood</td>
<td>tangential-fired PC Boiler</td>
<td>Full scale</td>
<td>TVA, Foster Wheeler</td>
<td>[176]</td>
</tr>
<tr>
<td>14</td>
<td>mold biomass pellets</td>
<td>300 MW pc-fired furnace</td>
<td>Pilot scale</td>
<td>Tan</td>
<td>[91]</td>
</tr>
<tr>
<td>15</td>
<td>Plastic/fiber waste</td>
<td>Pulverized Coal boiler</td>
<td>Full scale</td>
<td>South Carolina E&amp;G</td>
<td>[176]</td>
</tr>
<tr>
<td>16</td>
<td>25 wt% olive cake in coal mixture.</td>
<td>bubbling fluidized bed</td>
<td>Pilot scale</td>
<td>Atimtay</td>
<td>[183]</td>
</tr>
<tr>
<td>No.</td>
<td>Description</td>
<td>Technology</td>
<td>Scale</td>
<td>Organization/Reference</td>
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<td>-----------------------------------</td>
<td>----------</td>
<td>---------------------------------</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>High-percentage wood</td>
<td>pulverized coal boiler</td>
<td>Full scale</td>
<td>Savannah Electric and SCS [176]</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Wood co-firing</td>
<td>Cyclone boiler</td>
<td>Full scale</td>
<td>TVA, Foster Wheeler [176]</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Mid-percentage co-firing</td>
<td>pulverized coal boiler</td>
<td>Full scale</td>
<td>NYSEG [176]</td>
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</tr>
<tr>
<td>21</td>
<td>Wood and tire tri-firing with coal</td>
<td>Cyclone boiler</td>
<td>Full scale</td>
<td>TVA, Foster Wheeler [176]</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>straw and pulverized coal</td>
<td>2.5 MWt Power plant</td>
<td>pilot-scale</td>
<td>Pedersen [184]</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Wood co-firing up to 20% by mass</td>
<td>Cyclone boiler</td>
<td>Full scale</td>
<td>TVA, Foster Wheeler [176]</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>rice husk and bamboo</td>
<td>bench-scale reactor</td>
<td>Pilot scale</td>
<td>Y.H. Chao [185]</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>Sawdust, right-of-way and poplar</td>
<td>pulverized coal boiler</td>
<td>Full scale</td>
<td>GPU/Penelec, Foster Wheeler [176]</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>Olive cake firing</td>
<td>fluidised bed</td>
<td>Pilot scale</td>
<td>Cliffe [186]</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>Switch-grass co-firing</td>
<td>pulverized coal boiler</td>
<td>Full scale</td>
<td>University of Wisconsin [176]</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>straw and pulverized coal</td>
<td>250 MWe utility boiler</td>
<td>Full scale</td>
<td>Pedersen [184]</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>plastics, mill residues</td>
<td>pulverized coal boiler</td>
<td>Full scale</td>
<td>Duke Power [176]</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>Grass crops and wood crops</td>
<td>coal-fired power plant</td>
<td>Pilot scale</td>
<td>Iowa State University [176]</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>sawdust and coal</td>
<td>tangentially- fired furnace</td>
<td>Full scale</td>
<td>FORTUM’s Naantali-3 CHP [31]</td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>switch grass with coal</td>
<td>Bench-scale test</td>
<td>Pilot scale</td>
<td>DOE/PETC [176]</td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>Straw with coal</td>
<td>150MWe power station</td>
<td>Full scale</td>
<td>Wieck-Hansen [187]</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>Coal and Straw</td>
<td>150 MWe Utility PF-Boiler</td>
<td>Full scale</td>
<td>Danish energy company [188]</td>
<td></td>
</tr>
</tbody>
</table>
2.3. Co-firing of Low Rank Coal with Biomass

A number of experimental studies were conducted for the feasibility study of co-firing of biomass fuel in laboratory/pilot scale as well as industrial scale. These studies demonstrated highlighting the importance of co-firing concepts using different biomass with coal. Table 2.3 and Table 2.4 summarize the attempts taken for selected coal: biomass co-firing studies in small scale, lab scale and industrial scale studies. However in this work we will discuss in detail different types biomass, its ignition properties, burnout performance and emissions level etc.

The burning characteristics of different biomass based fuels resources from the Mediterranean region were studied experimentally in a thermo-gravimetric analysis system by Vamvuka [85]. To determine the performance of the processes, combustion parameters, ignition and combustion indices, combustion rate, oxidizer fractions, effects of particle size and shape, the amount of moisture content of the fuels was measured. It was found that the burning of the fuel was dominated by the production of volatile matter. There is a relation between the ignition and burnout temperatures, with the particle size and moisture content of the fuels. It was found that oxygen-enriched atmosphere improved the combustion temperature and the burnout time, and hence improved the plant performance. It was concluded that higher heating rate is responsible for the delay of the process leading to increase the overall burning rate. McIlveen [189] carried out a detailed investigation considering technical as well as environmental aspects for the co-firing of coal and biomass in a fluidised bed type structures for the reduction of carbon dioxide (CO$_2$) in a dedicated coal-fired power plant. In another study given in Ref. [190], experiments were conducted to investigate the combined combustion of
biomass and coal in power plant technology, with the blending of pulverized biomass with coal. Results showed that a comparatively higher burnout (up to 20% thermal input of biomass) was observed. Also, the effects of pyrolysis gas composition, stoichiometry, and residence time in the reaction zone were investigated, shows low CO emission (lower than 150 mg/m$^3$) and minimum NOx emissions (200 mg/m$^3$).

The combustion behaviour of Greek lignite co-fired with four biomass materials were investigated in the devolatilization stage by thermogravimetry [191]. The co-firing ratios were changed with the addition of 5, 10 and 20% wt. biomass in the fuel blends. The combustion environment was air-fired under dynamic conditions at a heating rate of 10 J°C/min. No significant results were observed in the process of solid coal-biomass pyrolysis under different co-firing ratios maintaining similar oxidizing conditions. A similar experimental study was carried out by Kakaras [192]. His study analysed the pyrolysis characteristics and related kinetics of biomass residuals mixtures with lignite. The outcome of the variations of material particle size and burning rate was studied. The temperature range was 25–850°C. Higher thermo-chemical reactivity was found for the biomass fuel compared to lignite. Also the consequence of the heating rate on the pyrolysis behaviour was prominent in biomass burning.

Naruse [193] conducted an experimental study for co-combustion of low-rank coal with biomass to approve on the basics of ignition, NOx emissions measurement and ash generation performance in a drop tube furnace which was heated electrically. A low pressure impactor was used to measure the particulate matter while gas composition was analysed to determine the species concentrations. It was suggested that addition of biomass with low-rank coal significantly affected the combustion performance from the ignition point of
view. But, there were no significant difference in the NOx generation analysis. A similar amount of NO and N2O were found in co-firing of biomass to only coal combustion, even if the amount of contributed fuel nitrogen under the co-combustion state was half of that under the coal combustion conditions. A similar study was conducted by Skodras [177]. He piloted the co-combustion of lignite–biomass–waste blends in a pilot scale incinerator. Their study concentrated on the compounds of toxic emissions during a series of co-combustion tests. The emissions level was measured for polychlorinated dibenzo-p-dioxins (PCDDs) and dibenzofurans (PCDFs). It was concluded that coal/biomass blends were proven to be useful as a good fuels and reproducible combustion conditions.

The effects of biomass injection momentum on the overall flame structure and pollutant emissions were experimentally explored in Ref. [194]. It identified the impact of co-firing of coal and biomass on the flame characteristics and stability. Different types of biomass such as Swedish wood, straw, palm kernels, wood pellets and high-protein biomass were co-fired with a common type of coal. The co-firing proportion of biomass was varied in the range of 0% to 20% by weight. The relationship between the flame temperatures and the primary combustion process were investigated. It was found that the variation of physical and chemical properties of the biomass fuels has direct impact on the characteristics of the flame for the variation of co-firing proportions. The main differences were observed in the flame ignition points and brightness. The flame stability was also affected by the addition of biomass (no more than 20%). Figure 2.3 shows a typical image and temperature distribution for a coal–biomass (coal and 10% palm kernels) flame.
In another study, Tan [91] piloted an experimental study using different type of biomass (mold biomass pellets) co-firing in a large scale (300 MW) coal-fired power plant in China. The goal of this investigation was to recognize the effects of co-firing mold pellets on the overall flame, temperature, pollutant emission, and amount of unburned carbon in ashes. The amount of biomass used with coal was in the range of 0-16.1% on the basis of energy input. Results showed that the flame temperature during the process of biomass injection was stable, but a reduction in the exit of the furnace temperature was observed. Though a temperature variation is located at different positions, the unburned carbon in ash increased significantly compared to the case with burning pulverized coal. At high feed rate of biomass of about 24 t/h, there was a drastic reduction of NOx emissions. Compared to NOx reduction (about 10%), the reduction in the SOx emission is very small. The output of this experimental study provided a simple guideline for biomass co-firing in a dedicated coal-based power plant.

Figure 2.3: Typical image of a coal–biomass flame and its temperature distribution (coal and 10% palm kernels) [194].
2.4. Performance of Various Biomass Co-firing

2.4.1. Straw Co-firing

Straw is one of the most available biomass in the environment. Considering its importance, Pedersen [184] conducted a detailed experiment on firing of straw co-fired with pulverized coal in a pilot scale (2.5 MWt) and a large scale (250 MWe) furnace. In the full scale experiment, fractions of straw in the range of 0-20% on a thermal basis were used. But in pilot scale experiment, 0-100% on a thermal basis was used. Two different concentration of sulfur coals were considered in the pilot scale, but only high-sulfur coal was used in full scale. Figure 2.4 shows the measured SO$_2$ emissions for both pilot- and full-scale experiments at different blending ratios. It is seen that increasing the straw fraction results in a decrease in the SO$_2$ emissions. This can partly be explained by the lower sulfur content of the straw. Also lower SOx emission was not only due to a lower S concentration in the straw but also for preservation of S in the ash. It was also investigated that raising the straw fraction in the blend was responsible for higher amount of volatiles release. In another analysis given in Ref. [187], co-firing coal with straw in a 150MWe power station, has been demonstrated. The goal of that study was to determine the impact of co-firing on plant’s performance, chemical reactions in the combustion, heat transfer performance, deposits on surfaces and the effects of corrosion, residual quantity and quality, emissions level and other catalytic reduction systems. Andersen [188] conducted another experiments which mainly highlighted the formation of deposits in a pilot-scale (150 MWe) utility boiler. In this study, the co-combustion of coal and straw at the Danish energy company I/S Midtkraft was conducted. The maximum fraction of straw used in this study was approximately 20% on energy basis. Different technique and measurement systems such as scanning electron microscopy (SEM), energy dispersive X-ray
analyses (SEM-EDX) and bulk chemical analyses were used for the determination of deposits formations and high temperature corrosion during co combustion.

2.4.2. Olive Cake Co-firing

In order to use the waste as an energy source, the co-firing of waste from olive oil production with coal was conducted in a fluidised bed by Cliffe [186]. It was found that compared to only coal combustion, Olive oil waste with up to 20% sharing can be co-fired with coal with a combustion efficiency of 5%. A similar type of performance was observed for CO emissions.

Figure 2.4: Emissions of SO$_2$ at various straw fractions in the coal straw blend. (adapted from [184]).
Atimtay [183] investigated the co-combustion of olive cake with coal in a bubbling type small fluidized bed (102 mm diameter and 900 mm height). Several operational parameters were tested such as excess air ratio, secondary air injection, emissions concentration and plant efficiency. It was observed in the test that the most favourable operating environment with respect to emissions level (NOx and SOx) was originated to be 1.35 for excess air ratio, and 30 L/min for secondary air flow rate. These were achieved for the combustion of 75 wt% olive cake and 25 wt% coal mixture. The maximum combustion efficiency of 99.8% was attained with an excess air ratio of 1.7, secondary air flow rate of 40 L/min for the combustion of 25 wt% olive cake and 75 wt% coal mixture.

**Figure 2.5**: Ash mass flow and fine particulate matter concentrations.

(adapted from [179]).
2.4.3. Municipal Solid Waste Co-firing

Suksankraisorn [178] conducted the experiment on co-firing of municipal solid waste (MSW) containing high moisture and Thai lignite containing high sulfur in a lab scale bubbling fluidized bed which measured the effects of the mass concentration of a model MSW in the fuel mixture on the combustion characteristics for 100% lignite. The findings are demonstrated in terms of flame temperature distributions, combustion efficiency and concentrations of the pollutants such as CO$_2$, CO, SOx and NOx etc. The outcomes indicate that for utilization of 40% MSW fraction, combustion efficiency drop of up to 8%. It was concluded that for the experimental cases, the best possible condition for co-firing in terms of burning efficiency and emissions level (CO, NO and N$_2$O emissions) was to use 20% MSW fraction with 40% excess air and secondary to total ratio was 0.2. Wolski [179] studied the particle formation for co-combustion of two different fuels to determine the impact of the additional fuel sewage sludge on fine particle matter experimentally at 300 kW test facility. This investigation provides an understandable sign on the constructive outcome of co-combustion. Depicted in Figure 2.5 are the concentrations of the overall particulate matter as ash mass flow and particulate matter concentrations of both overall and fine fraction. It was found that the an increase in the percentage of sewage sludge fraction of the overall energy contribution resulted in overall higher ash amount and also provided a decrease of the finest particulate matter concentration (< 1 micro m) in the flue gas [190].
2.4.4. Miscanthus Co-firing

Wagenaar, in his study [88], demonstrated the process of devolatilization for Miscanthus fuel in a pulverised coal combustion chamber. The aim of this study was to find the conditions at which the coal and Miscanthus have similar value of devolatilization rate. The test was conducted for the high-temperature Miscanthus decomposition in the drop tube. It was shown that that particle having small sizes (0.6-1 mm) would be devolatilised completely in a 1.6 m long drop tube. Another study [180] reported about the emissions of unburned hydrocarbon (HC) species from batch combustion of coal, sugar-cane bagasse, and blends. For this study, a pre-heated two-stage laboratory furnace of fixed bed type was used. The typical input fuel/air equivalence ratios were parallel for all fuels. The furnace temperatures were varied from 800°C to 1000°C for primary and secondary inlets. The impacts of fuel mixing, burning staging, and operating reactor wall temperatures on the emissions for all the fuels were
evaluated. Reactor effluents were assessed for carbon dioxide (CO$_2$) and specially carbon monoxide (CO), volatile matters and semi-volatile hydrocarbons (HC) and for the particles. Results showed that the emission of CO$_2$ was found during both the observed sequential volatile matter and char combustion phases of the fuels but emission of CO was only found during the devolatilization process. Also the levels of CO$_2$ emissions were the maximum for coal combustion but CO emissions were the maximum for bagasse burning. The integrated emissions of CO$_2$ and CO emitted during the combustion of the volatile matter are shown in Figure 2.6, normalized by the mass of volatile matter in the fuels.

2.4.5. Rice Husk Co-firing

Compared to biomass fuel particles, several researchers considered rice husk as a co-combustion fuel. Rice husk is a by-product of the rice-milling process which is one of the most potentially sustainable biomasses in Asian countries. Chao [185] studied the applicability of using rice husk and bamboo to fire with coal in a bench-scale pulverized fuel combustion reactor. During the experiment, the following parameters were considered, biomass blending ratio, biomass size, air ratio and moisture content. It was found that an operation range of 10-30% of biomass to coal ratio was the optimum range for minimum pollutant emissions. It was seen that higher volatile matter content in the biomass fuels was responsible for improving the combustion performance. Haykiri-Acma [195] worked on co-firing of low rank coal with waste biomass using rice husk and the olive milling residue using at differential thermal analysis (DTA) and derivative thermo gravimetric (DTG) analysis. Madhiyanon [181] conducted a similar type of experimental study to investigate the combustion characteristics of firing rice husk mixing with coal (bituminous type) in a small scale (120 kWth) cyclonic fluidized-bed combustor (FBC) located in Thailand. In the same time, Li [182] conducted a comprehensive
study to determine the NO reduction in decoupling combustion of Biomass and biomass-coal blend in a quartz dual-bed reactor. This study investigated that NO emissions during using biomass and also biomass-coal blends produced comparatively lower emission than only coal combustion. Also, it was observed that with the increase of biomass sharing, the NO emission from burning of blends of biomass and coal were significantly reduced. Using rice husk co-fired with coal in a small scale 10 kW stove using the decoupling combustion technology reinforced results which were meaningful for exceptionally low NO emission with higher efficiency for combustion of biomass and biomass-coal blends, no matter about the size or capacity of the boiler/reactor.

2.4.6. Woody Particle Firing

A comprehensive study was conducted considering coal and saw dust in a tangentially-fired pulverized-coal unit of FORTUM’s Naantali-3 CHP power plant which has the capacity of 79 MW electricity, 124 MW district heat and 70 MW steam [31]. This is equipped with the modern technologies such as roller coal mills, modern low-NOx-burners, over-fire air (OFA), electrostatic precipitator (ESP) and flue-gas desulphurization plant (FGD). The coal/saw dust blend was prepared in the coal yard and supplied to the boiler through coal mills. The outcome of this study indicated that by using this concept the substitutions of 5–30% (on the basis of fuel input) coal is possible by biomass type fuels.

Later, Zhang [72] in a similar type of study used woody biomass, cedar chip in a lab-scale drop tube furnace. The objective of this study was to look into the synergetic relations between the inorganic elements of the selected fuels and the level of emissions of sub-micron particles (particles < 1.0 lm in size, PM1) and super micron particles (particles in the size range of 1.0–10 lm, PM1+). The blend of cedar chip with coal was maintained using 10% to 50% of biomass on
mass basis. Air-firing was considered for all the fuels ratios at furnace temperatures of 1200°C and 1450°C. The principle effect of this study indicated that, under an indistinguishable calorific input, burning of the biomass enhanced the formation of emission of PM1 particles. Microstructures of typical coarse ash particles generated from combustion of different fuels in Figure 2.7 indicated the significant interaction between inorganic constituents during co-firing. The contents of emissions were largely comprised of volatile elements such as K, Ca, Fe, Na and P. When a small fraction (10%) of cedar chip was supplied, there was less effect of the interaction between the inorganic elements of single fuels at any selected furnace temperature. But a noteworthy impact was achieved during co-firing of >10% cedar chip with coal at the temperature of 1450°C. Another study [84] investigated the effect of co-firing of woody biomass residues of sugarcane bagasse with pulverized coal with different ranks. Pyrolysis was conducted using three-color pyrometry and high-speed high-resolution cinematography and the significant changes were observed during char processing. It was experienced with the process of softening, melting, swelling etc.

2.5. Environmental Aspects of Co-firing

Co-combustion of biomass with coal has a substantial effect on SOx and NOx emissions level. It is seen in all the studies that SOx emissions normally decreased uniformly when biomass is co-fired with coal. This is because the biomass contains comparatively less sulphur (S) than coal maintaining the proportional balance on thermal load.
Figure 2.7: The formation of NOx in biomass combustion [47].

Also, a greater reduction is predicted during sulphur retention by alkali and alkaline earth compounds in the biomass fuels. The impact of co-firing biomass with coal on NOx emissions are more challenging to predict. As NOx and SOx emissions from biomass co-firing is seen in general to be low compared to those from fossil fuel combustion, it is not necessary to use supplementary reduction techniques to control the level of emission limits. NOx emissions generally originate from the nitrogen content during the applications of biomass combustion, and N₂ in the air also contributed to the NOx emission level. The basic concept of NOx generation is given in Figure 2.8. Normally, the level of NOx emission is possible to reduce significantly using primary emission reduction technique, and further reduction is possible implementing secondary emission reduction measures. But in small-scale power plant based on natural draft contributed major portion of emissions level due to incomplete combustion.

For these small scale units, controlling the emissions from combustion process are not cost-effective. Emission monitoring has been done in a 13.8 MWth
industrial power plant using Greek Lignite co-fired with natural waste wood in [196]. The outcome of this study showed that co-firing is technically viable provided that agglomeration problems could be confronted. Lower levels of emissions below the regulation values were found during the tests. In solid ash samples, iron was found while zinc was located in the flue gas. Another system for monitoring the emissions level was presented in [54] and this model was assumed to be appropriate for the visualization of deposit tendencies, and the ability to determine the influence of ash deposit on heat transfer.

The emissions of VOCs in co-firing of several wastes with coal were investigated by Gulyurtlu [161] in a pilot-scale fluidized bed combustor. This study demonstrated that the key parameters for the formation of VOCs are, temperature, excess air levels, and the effectiveness of the mixing of air with fuel. Also it was indicated that biomass was not the main source of VOCs. The volatile released from the biomass fuel responsible for the reduction of VOCs was almost zero. Badour and Gilbertetal [51] investigated the pollutant emissions during co-firing a Canadian lignite coal with a Canadian peat and a woody biomass in a BFBC boiler. The NOx and SO$_2$ emissions level were determined when peat pellets or pine pellets were mixed and fired together with lignite at 0%, 20%, 50%, 80%, and 100% on a thermal basis. The graphical representation of the effect of co-firing on NOx and SOx emissions are given in Figure 2.9. Co-firing of biomass decreased both NOx and SO$_2$ emissions. As with the influence of biomass fuels on NOx emissions, SOx emission levels gradually reduce as the amount of biomass fuel co-fired with coal increases [49].
Figure 2.8: The effects of lignite-peat co-firing and lignite-white pine co-firing on NOx and SO2 emissions (adapted from [51]).

2.6. Ash Formation and Deposition

The by-product of the combustion process is the fly ash from the power plant. Most of the fly ash produced in the coal-fired power plant throughout the world is used as a concrete additive or for other purposes. But it is still not appropriate to use fly ash from co-firing wood with coal. Literature suggested that herbaceous biomass fuels which contain alkali, chorine, and other properties may compromise several important concrete properties. There is not enough evidence to preclude the fly ash from biomass energy source for the supply of concrete additive. Ash deposition rates of biomass fuel are significantly varied compared to only coal combustion. This is partly attributable to the total ash amount of the fuels. The rate of deposition from blends of coal and biomass are generally lower than indicated by a direct interpolation between the two rates.
Several studies have been performed to determine the ashing process, fly ash quality during co-combustion. It is known that the fly ash properties basically depend on several factors such as conversion technology, capture technology and fuel properties. Co-firing of domestic residual such as dung from cattle was investigated by Annamalai et al. [198] and Sweeten et al. [199]. In these studies no specific information about the properties of the generated fly ash was reported. But a guideline is demonstrated to show the ties of co-combustion fly ash to the characteristics of the fuel and the related process. It was also shown that a very good quality of fly ash is generated to meet the European standard during the co-firing of higher percentage (up to 33%) of biomass fuel. The ashing process during straw/coal co-firing was examined in an experimental
study in Ref. [197]. The objective of this study was to evaluate the effect of the blending ratio on the overall ash products. A series of blending ratios were considered (coal content 5 wt. % to 90 wt. %). In order to determine the ash fusion temperature, oxide concentrations and the amount of mineral, pure coal and pure straw was also tested in separate experiments. The blends of 5 wt. % and 15 wt. % coal were shown to reduce ash with a coal fraction greater than 20 wt. %, the ash quantity increased. Pyrolysis and thermal decomposition were also analysed for blends with 10 wt. % and 40 wt. %, as well as pure coal and pure wheat straw. It was found that the ashing processes was significantly dependent to the coupling reactions of the minerals contained in the straw and coal. More potassium (K) was discharged into gaseous medium at the time of devolatilization of co-firing of blend of 10 wt. % coal. Figure 2.10 shows a typical microscopic view of the ashes from different fuels such as straw, coal and blend with 10 wt.% coal and blends with 40 wt.% coal taken from the experimental study of Wang [197]. It is seen from the figure that ash produced from straw is a regular fibre bundle in shape with some white fusing mineral particles. On the other hand, the ashes produced from coal particles were regular in shape. But the blends with 10 wt. % coal showed a combination of scattered fibre-shaped particles with some confined fusion going on in ash particles. But, there were zero particles in the fusion process for the case of 40 wt% blend. It was also noted that when the temperature was increased due to the release of some volatile matter and later the combustion occurred. A similar study conducted by Saraber [200] in a 1 MWth test boiler demonstrated the co-firing coal and poultry dung, demolition wood and solid recovered fuels . This study extensively identified the relation of co-combustion and fly ash quality and determined the amount of fly ash generated during the process. Table 2.5 presented typical composition of concentration of macro compounds, trace elements of the generated fly ashes.
Table 2.5: A typical composition of concentration of macro compounds, trace elements of the generated fly ashes [200]

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### Concentration of trace elements in the generated fly ashes (mg/kg)

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<tr>
<td>Mo</td>
<td>24</td>
<td>22</td>
<td>24</td>
<td>23</td>
<td>25</td>
<td>22</td>
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<td>3604</td>
<td>1074</td>
<td>1229</td>
<td>1449</td>
</tr>
</tbody>
</table>
Table 2.6: Fly ash analysis (% by weight) [201]

<table>
<thead>
<tr>
<th>Coal/biomass ratio</th>
<th>Unburned carbon</th>
<th>Volatile matter</th>
<th>Inert matter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neat coal</td>
<td>29.23</td>
<td>5.07</td>
<td>65.70</td>
</tr>
<tr>
<td>Coal + 5% biomass</td>
<td>25.63</td>
<td>3.57</td>
<td>70.80</td>
</tr>
<tr>
<td>Coal + 10% biomass</td>
<td>24.54</td>
<td>3.86</td>
<td>71.60</td>
</tr>
<tr>
<td>Coal + 15% biomass</td>
<td>12.95</td>
<td>3.85</td>
<td>83.20</td>
</tr>
<tr>
<td>Coal + 20% biomass</td>
<td>08.84</td>
<td>3.96</td>
<td>--</td>
</tr>
</tbody>
</table>

2.7. Effects of Co-firing Ratios

It is vital to determine the optimum co-firing ratios for selected combustion cases considering cost and performance of the plant. Suggestion and recommendation for the maximum level of biomass with specific data of particle size and fuel properties is needed. In order to control the furnace efficiency and production, the effect of biomass injection rate, thermal and fluid-dynamic behaviour and the design of the burner are also important. Rudiger [190] suggested that comparatively higher burnout was observed with up to 20% thermal input of biomass. The effects of biomass injection momentum on the overall flame structure and pollutant emissions were experimentally explored in Ref. [194] using Swedish wood, straw, palm kernels, wood pellets and high-protein biomass co-fired with a common type of coal. It was found that the variation of physical and chemical properties of the biomass fuels had a direct impact on the characteristics of the flame for the variation of co-firing proportions. The main differences were observed in the flame ignition points and brightness. The flame stability was also affected by the addition of biomass (no more than 20%).
A similar study [202] investigated the effect of multi-fuel burner configuration for co-firing cereal and straw with coal and the level of NOx emissions for different burner configurations were evaluated. Figure 2.11 shows the effects of multi-fuel burner configuration used and the generated emissions. In another study, Tan [91] piloted an experimental study in a large scale (300 MW) coal-fired power plant showing that the amount of biomass used with coal was in
the range of 0-16.1% on the basis of energy input which provided a stable flame temperature during the process of biomass injection. At a high feed rate of biomass of about 24 t/h, there was a drastic reduction of NOx emissions. Compared to NOx reduction (about 10%), reduction in the SOx emission is very small. The output of this experimental study provided a simple guide for biomass co-firing in a dedicated coal-based power plant.

Suksankraisorn [178] highlighted the effect of co-firing ratios for municipal solid waste (MSW) combustion in a lab scale bubbling fluidized bed. The findings are illustrated in terms of flame temperature distributions, combustion efficiency and concentrations of the pollutants such as CO\textsubscript{2}, CO, SOx and NOx etc. The outcomes indicated that for utilization of 40% MSW fraction, combustion efficiency drop up to 8%. The study of Wolski [179] performed in a 300 kW test facility suggested that the best possible condition for co-firing in terms of burning efficiency and emissions level (CO, NO and N\textsubscript{2}O emissions) was to use 20% MSW fraction with 40% excess air and a secondary to total ratio was 0.2. Compared to biomass fuel particles, several researchers studied the suitability of optimum rice husk co-firing possibility. Chao [185] studied the applicability of using rice husk and bamboo to fire with coal in a bench-scale pulverized fuel combustion reactor. It was found that an operation range of 10-30% of biomass to coal ratio was the optimum range for minimum pollutant emissions. The studies performed at the unit of FORTUM’s Naantali-3 CHP power plant [31] indicated that by using this concept, substitutions of 5–30% (on the basis of fuel input) coal is possible by biomass type fuels. Table 2.6 represented the effects of co-firing ratios on the fly ash components. It is seen that for all the situations, the change of coal to biomass co-firing, improved effects were characterized. Table 2.6 summarised the concentrations of the unburned carbon and inert matter in the fly ash collected from the flue section of the furnace. It has been found that the quantity of the unburned carbon is
excessively high (up to 30%) in comparison with other pulverised coal fired furnaces. indicates that the quantity of unburned carbon decreases with biomass addition. In other words, the co-firing of biomass and coal would help to reduce unburned carbon in the fly ash, and thus improve the efficiency. This situation suggests that the biomass with high volatile content would help the combustion of the low quality coal.

2.8. Adoption of Oxy-fuel Co-firing

Oxy-fuel combustion is termed as a GHG abatement technology. In this technology, fuel is combusted with the aid of mixture of oxidizer and recycled flue gas provided a rich stream of CO$_2$ [195]. This technology is widely used for coal combustion [12, 22, 203, 204], but limited attempts were taken for the biomass co-firing cases. Recent studies concentrated on these issues to investigate the effect of oxy-fuel combustion in co-firing in details. An experiment was done in an entrained flow reactor [126] to burn coal and biomass in oxy-fuel cases. The goal of this study was to evaluate the ignition and burnout performance of the used fuels. It showed that the ignition temperature of coals had strong dependence on the combustion environment. A delay in the ignition was observed for the burning at a mixture of 79\% CO$_2$–21\% O$_2$ compared with air-firing. This significantly affected the flame temperatures. When the O$_2$ fraction in the CO$_2$/O$_2$ mixture is higher than 30\%, early ignition take place at comparatively lower temperatures. The ignition of coal particle in air-firing is rich because of the addition of biomass in the blend. It was concluded that use of biomass blend has a low impact during air combustion. But, significant improvement in the burnout of the coal/biomass blends was found under oxy-fuel co-combustion.
The 0.5MWth combustion test facility (CTF) used in the study of Smart [205-207], located in Didcot, UK considered the air and recycled flue gas (RFG) combustion cases. This facility is equipped for coal combustion under air and oxy-fuel conditions. References [205-207] discussed the experimental investigations of the effect of radiative and convective heat transfer and burnout effects of Russian coal and South African coal with different recycled ratios (RR) and the co-combustion of highly volatile coal with 20% Saw dust and 20% Shea Meal under different combustion environment. The recycled ratios (RR) considered in this experimental study were RR65 % (total O$_2$ 30.9 % and total CO$_2$ 69.2 % by mass), RR72 % (total O$_2$ 25.4 % and total CO$_2$ 74.6 % by mass) and RR75 % (total O$_2$ 22.8 % and total CO$_2$ 77.2 % by mass). Radiative heat flux was measured on the side wall at different location. In measuring the surface incident radiation (SIR), a MEDTHERM digital heat flux meter was used. Measured radiative heat transfers are presented in Figures 2.12-2.13.

Yaman [208] used TGA and DSC techniques to determine the thermal reactivity and overall burnout characteristics using sunflower seed shell and hazelnut shell co-fired with Soma–Denis lignite. There was a significant variation in the characteristics of thermal reactivities between coal and biomass fuel under different combustion environment. Based on this study, the co-firing of coal/biomass mixtures under oxygen was suggested as an alternative method to the carbon dioxide recycled method which is related to the oxy-fuel combustion systems. Skeen [209] investigated the NOx emissions in a laboratory scale (30kWth) test facility using river basin coal co-fired with sawdust under air and oxy-fuel environment. Riaza [210] conducted the investigation on oxy-fuel co-firing of coal and biomass blends to determine the flame temperature, carbon burnout and NOx emissions. As a fuel, a blend of a semi-anthracite bituminous coal with 10-20 wt. % of olive waste in a flow reactor was considered. Results indicated that replacement of N$_2$ by CO$_2$ in the oxidizing environment with 21%
of O₂ increases the temperature of ignition. When the concentration of O₂ increases to 30-35%, a higher burnout was found compared to air-firing. It was also found that when the biomass sharing is increased, a decrease in the ignition temperature and rise in the burnout value was predicted.

Another recent study [211] presented some new findings on the impact of combining biomass co-firing with SNCR under various oxygen enriched and air-staging conditions. This study was performed experimentally in a laboratory scale of 20 kW combustion test facility. Biomass has the ability to generate higher amount of CO and to reduce the level of NOx emission with and without using SNCR. It is seen in the experiment that the percentage of NOx reduction was around 80% using SNCR for 15% and 50% of biomasses at oxy-fuel case (21% O₂) for unstaged combustion. Whereas 40–80% NOx were reduced for coal and 15% co-fired biomasses at O₂ level of 22–31% considering flame staging. It was concluded that improved NOx removal efficiency was detected for higher NOx emission baselines under both air-firing and oxy-fuel environments.
Figure 2.11: Measured radiative heat flux distribution for different biomass sharing under air and RR75 cases (adapted from [205]).
Figure 2.12: Measured radiative heat flux distribution for different biomass sharing under RR 68 and RR 72 cases (adapted from [205]).
2.9. Development of Co-firing Modelling Concept

As biomass is considered a carbon-based renewable fuel, it is termed as the most applicable energy source for climate protection. Compared to traditional combustion modelling, basics, significant factors such as the variation of biomass size and shapes (spherical/irregular), and complex measures for emissions need to be considered in computational modelling [42]. A comprehensive review of the current status of sub-models available for the coal combustion is given in [11-13, 79, 127, 129, 212-214]. Most of these sub-models available for coal are applicable to for biomass combustion although there are still some features which need further development [204, 215]. Williams [43] demonstrated a CFD code for co-firing of biomass and coal and further research showed the benefits of this concept for the reduction of carbon footprint of energy production [82]. It is essential to model co-fired furnaces in order to explore the potential outcome that may happen during co-firing of biomass.

2.9.1. Effects of Particle Size Distributions

The variation of biomass fuel particle shape has a significant impact on the performance of the combustion efficiency. Biomass particles are found in different irregular shapes for utilization in the power plant. In most of the CFD studies, biomass particles are assumed to be spherical in shape, whereas only few studies considered the non-sphericity of the biomass type fuel. A computational study given in Ref. [36] was conducted considering effects of co-firing biomass with coal where straw particles were introduced as co-fired fuel. Coal and straw particles were assumed to be spherical in shape. In this study, straw was mixed with coal as 10 and 20% on thermal basis. For the reaction modelling, two-mixture fractions approach is considered while particles dispersion due to turbulence in the gas phase is evaluated considering
stochastic tracking model. However, the main limitation of this study was to avoid the shape effect of irregular particles. Similar to previous studies, a comprehensive CFD modelling for determining heat transfer using biomass particles is given in Ref. [216].

Available CFD codes ignore thermal gradients of the particles lead to inaccuracies for the modelling. Hence, the effect of particle shape and thermal gradients of irregular shaped biomass particles on the emissions level (coal based CO₂ emissions and biomass based SOx and NOx emissions), flame temperatures were evaluated. Also, the impact of fuel particle sizes distribution on ignition characteristics such as ignition, the process of devolatilization and char combustion. Consideration of internal gradient with particle size and shape was proved as an excellent addition in modelling.

The models used to simulate the solid fuel combustion are dependent on the assumption of sphericity which may deviate a lot from reality for large biomass particles. In order to understand the biomass combustion as well as to upgrade the design of the furnace, non-sphericity of particle is considered in the study of Yin [217]. Also a comparison of the consideration of sphericity and non-sphericity were also taken into account. For the comparison, two different cases were numerically simulated in a 10 m co-fired furnace. The numerical prediction showed that there was significant variation between the cases of hollow cylinders and spherical volumes. It was suggested that it is very important to consider the non-sphericity of biomass particles for correct modelling of the combustion.
Figure 2.13: Comparison of predicted trajectories for biomass particles modelled as cylinders or spheres of equal volume [75].

Karampinis [92] studied another 3D modelling for co-firing of lignite with biomass in large-scale utility boilers of 300 MWe tangentially fired boiler situated in Northern Greece. The non-sphericity of the biomass particles were taken into account for the modelling and influence of the drag coefficient and the process of devolatilization and combustion mechanisms were evaluated.

When biomass particle is large in size, there is a chance for incomplete combustion. Williams [32] conducted a computational study to examine the co-firing of larger diameter biomass particles burnout. Necessary sub-models were developed for chemical reactions and the source term for different type of fuels. It was found that smaller (200 µm) wood particles participated in quick combustion, but the rate of combustion for the larger particles was dependent on several factors such as composition, size, and shape. The parameters used for consideration of irregularities of shape and size of the biomass particles combustion in different CFD studies are given in [218, 219]. Another numerical model for the combustion of pure biomass in industrial scale furnaces has been developed by Ma [80]. Studies of this kind can provide a base for all co-firing
applications. Detailed co-firing models have been developed using a CFD code considering Eulerian–Lagrangian approach. Special attention was given for the combustion of the larger and irregular biomass particles and promising results were found even though larger and irregular size of the particles was an issue which was handled adequately by the developed CFD model. It was concluded that presence of these irregular larger sized biomass particles affected the particle reactivity and aerodynamic behaviour in the furnace [80, 82]. A recent study [75] shows the variation of different types of biomass size used in CFD modelling. Figure 2.14 shows the comparison of predicted trajectories for biomass particles modelled as cylinders or spheres of equal volume.

Figure 2.14: Experimental flame temperature distributions for different co-firing cases [220]
Table 2.7: Examples of kinetic data and parameters used in the literature.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Heat rate</th>
<th>Temperature (°C)</th>
<th>A (1/s)</th>
<th>E (kJ/g mol)</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hazel nut</td>
<td>2°C/s</td>
<td>–</td>
<td>4.69×10^{13}</td>
<td>89.8–128.6</td>
<td>[221]</td>
</tr>
<tr>
<td>Rice husk</td>
<td>100°C/min</td>
<td>225–350</td>
<td>1.30×10^9</td>
<td>97.1</td>
<td>[221]</td>
</tr>
<tr>
<td>Rice husk</td>
<td>100°C/min</td>
<td>350–600</td>
<td>1.31×10^1</td>
<td>11.2</td>
<td>[221]</td>
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<td>Forest wood</td>
<td>2°C/s</td>
<td>225–325</td>
<td>7.68×10^7</td>
<td>124.8</td>
<td>[222]</td>
</tr>
<tr>
<td>Forest wood</td>
<td>2°C/s</td>
<td>700–900</td>
<td>6.32×10^2</td>
<td>92.3</td>
<td>[222]</td>
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<td>0.83°C/s</td>
<td>300–1123</td>
<td>2.15×10^3</td>
<td>59.4</td>
<td>[223]</td>
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<tr>
<td>Cellulose</td>
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<td>280–350</td>
<td>4.69×10^5</td>
<td>82.7</td>
<td>[224]</td>
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<tr>
<td>Lignin</td>
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<td>390–500</td>
<td>2.10×10^5</td>
<td>70.7</td>
<td>[224]</td>
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<td>320–400</td>
<td>8.70×10^2</td>
<td>33.8</td>
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<td>-</td>
<td>1.00×10^6</td>
<td>74.8</td>
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<td>Cynara</td>
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<td>-</td>
<td>9.00×10^{18}</td>
<td>239</td>
<td>[226]</td>
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<td>Shea meal</td>
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<td>6.00×10^{13}</td>
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<td>Woody biomass</td>
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<td>-</td>
<td>6.00×10^{13}</td>
<td>250</td>
<td>[86]</td>
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</table>

2.9.2. Effect of Flame/Gas-phase Temperatures

Using CFD modelling, a comparison of the flame temperature predictions for co-firing of coal and sawdust in different cases in a pilot scale furnace was given in [227]. The effect of wood co-firing injection strategies were evaluated considering two injection schemes. The simulated results produced temperature fields successfully compared with measurements for both injection strategies and various co-firing ratios. A comparison of experimental to numerical flame temperature taken from [228]. The flame temperature distributions for different co-combustion ratio under different combustion environment were investigated for co-firing of straw and coal in a 30 kWth combustion test facility [220]. These figures highlight the effects of variation of biomass sharing in respective combustion cases. Biomass contains higher volatile contents compared to coal. So, in case of air-firing, biomass burns early in the furnace because of the presence of highly volatile matters. With the increase of biomass to 50%, the
flame temperature expands more compared to 20% sharing because of higher percentage of volatile contents. Though higher amount of volatile contents correspond to larger volume of flame in oxy-fuel cases, higher moisture content and larger particle sizes of straw tend to decrease the peak flame temperature. The flame temperature distributions are presented in Figure 2.15.

2.9.3. Effects of Chemical of Reactions

The appropriate chemical reactions modelling for homogeneous and heterogeneous processes are important in CFD. The multi-steps reactions for devolatilization and char oxidation modelling is presented in Ref. [95]. A number of studies were conducted considering different types of chemical reactions. A large scale coal/straw co-firing in a utility boiler was modelled by Kaer [229]. In his study, a two steps gas phase combustion modelling was considered including chemical kinetics and a kinetic-diffusion model. The results showed a noticeable change compared to single step reaction modelling in the combustion behaviour such as temperature, species concentration, etc. In the study of Al-Abbas [95], three-step reactions have been considered for the combustion process of hydrocarbon (HC) fuel due to some limitations observed in single-step reaction scheme [96, 230]. In the presence of CO₂ and H₂O, a three step scheme is appropriate for the air-firing case as well as the oxy-firing case. As Global power law (one-step reaction) [98] cannot precisely capture the effect of the temperature and oxygen partial pressure dependency on the char combustion kinetics and CO/CO₂ production rate. Hurt and Calo [98] developed a multistep semi global kinetics char combustion model, and recently Nikolopoulos et al. [16] implemented in numerical code. Al-Abbas [95] investigated the effects of different char combustion model using single step and multistep (two steps and three steps) reaction mechanisms in a small scale furnace. Based on previous studies of the authors [62, 95, 96, 99, 100, 230], the two step reaction mechanism is used in the work of [95] since it was found to be
appropriate for modelling the char combustion process in a small scale furnace. Table 2.7 shows some examples of kinetic data and parameters used in the literature. Yin [71] considered the global four-step mechanism of Jones and Lindstedt [231] to be better in modelling volatiles combustion, and suggested that biomass particles of a few hundred microns in diameter and the intra-particle heat and mass transfer is a secondary issue at most in their conversion.

Figure 2.15: Contour of the species concentration in the riser [232].
2.9.4. Formation of Gaseous Pollutants

Axelbaum [209] formulated a CFD model to determine the cause and status of emission level and to recognize the differences between air-firing and oxy-fuel co-firing conditions in a laboratory scale furnace (30 kWth). It was found that co-fired flames spread a larger volume which is characterized by the increased volatile fraction and particle size associated with the biomass. A 3D CFD model was developed for co-firing different type of fuel called paper sludge in a typical fluidized bed boiler by Yu [233]. The results indicated that the combustion of paper sludge/coal is intensive at the lower part of the bed, at maximum value of 1400 K. It was shown that paper sludge spout introduced through the recycle inlet into the reactor will increase the flame temperature. It was predicted that 15% mass of sludge co-firing will provide highest temperature at the flue gas outlet. Wei [52] developed a numerical model to measure the amount of emissions level of species such as CO, NOx, and SOx formation during co-firing of different types of biomass including Swedish wood, Danish straw, and sewage sludge. It was established that there was a direct relation between the formation of NOx and the furnace temperatures. It was also found that firing biomass with coal could reduce the pollutant emissions. For pollutant free emissions, biomass with low concentration of N2 and S, a high volatile content with lower heating value is suggested as ideal co-firing condition. Recently, Zhong [232] presented a comprehensive three-dimensional CFD modelling highlighting the detailed emissions of olive cake combustion in CFB. Figure 2.16 shows the Contours of species composition profiles inside the riser.

2.9.5. Selection of Optimum Co-firing Ratios

It is vital to determine the optimum co-firing ratios for selected combustion cases considering cost and performance of the plant. Important parameters to
consider include maximum level of biomass sharing with specific information of particle size and fuel properties. In order to control the furnace efficiency and production, the effects of biomass injection rate, thermal and fluid-dynamic behaviour and the design of the burner are also important. Pallarés [83] studied a CFD analysis of co-firing coal and Cynara Cardunculus in a 350 MWe large scale utility boiler to consider the factors connected to the biomass feeding situation, e.g. biomass means particle size, level of sharing of coal by biomass and inlet location in the furnace. Though the author discussed influencing factors in details, no specific co-firing ratio was determined.

Arias [126] analysed the consequence of biomass blending on coal combustion during oxy-fuel burning of the mixtures of CO$_2$/O$_2$ of different concentrations. In this study, it was found that at an O$_2$ level of 30% or higher, better ignition was predicted and the combination of biomass with coal significantly improve the ignition characteristics in air. The burnout of blended coal of concentration of 79% CO$_2$–21% O$_2$ is lower than in air, where a change is seen when the oxygen concentration is higher. Ghenai [234] analysed the effects of co-firing of 5–20% wheat straw (thermal basis) with coal using CFD modelling. This CFD analysis highlighted the effect of the percentage of biomass blended with coal on the flow field, gas and particle temperature distribution, particles trajectories and gas emissions (CO$_2$ and NOx) were found. Also, the reduction of emission of NOx and CO$_2$ were observed. It was shown that reduction of the pollutant level is directly proportional to the sharing of biomass (wheat/straw) mixed with coal. A comprehensive modelling study was presented by Higgins given in Ref. [235] to design the ROFA system and to identify the accurate elevation for the burners for biomass burning. The effect of air pressure at the nozzles, aspect ratio (length/width ratio), and non-spherical shape factor were evaluated for controlling the furnace efficiency.
Ma [73] developed a CFD model for coal/straw burning in a similar type of furnace. In his study, by using particle heat-up model for consideration of the influence of thermal gradients, the suggested level of straw sharing of 12% on thermal basis was suggested. The effects of different sizes of biomass particles having irregular shape were also analysed. Levendis [84], suggested an optimum co-firing ratio using 30% sawdust could provide maximum particle burnout with minimum NOx emission. This study evaluated the effects of flame ignition, combustion aerodynamics and pollutant emissions using waste-derived solid fuels in a 0.5 MW down-fired furnace. A recent study by Alvarez [158] shows the effect of co-firing ratios on the temperature distribution, burning rate and NO emission for different co-firing ratios under oxy-fuel conditions. Figure 2.17 shows the predicted temperature distribution, burning rate and NO formation for different co-firing cases under oxy-fuel (35%O₂/65%CO₂) condition.
2.9.6. Effects of Heat Transfer Performance

Determination of heat transfer performance during the co-firing of biomass in a power plant furnace is important to evaluate the efficiency of the system. Recently, Black [128] conducted CFD studies to represent the heat transfer characteristics in a large scale power plant utilizing biomass under air-firing and oxy-firing cases. The authors also compared the heat transfer characteristics in different section of the convective zone of the furnace. It was concluded that overall >100MW heat is found in the coal combustion case under different combustion environment. The rise in heat transfer can be related to the increase in temperature within the furnace. As the temperature in the furnace section increases, it is expected to increase the heat transfer to the water walls. The characteristics in the platen superheaters also increase. Prediction of heat transfer (MW) for coal and biomass firing under OF25 and OF30 cases compared with air–firing cases are presented in Figure 2.18.

2.9.7. Retrofitting Air/ Oxy-fuel Co-firing

For a large scale power plant, it is difficult to perform experimental work on biomass co-firing concepts in a dedicated coal firing furnace, as it will also lead to the interruption of regular generation of power. Retrofitting a large scale dedicated power plant boiler is expensive. In order to retrofit a dedicated coal-fired boiler, matching in the performance of radiative, convective heat transfer and flame temperature is important. However, it is suggested that all the parameter profiles of oxy-fuel cases need to match as much as possible to air combustion for the retrofitting case. With proper selection of O\textsubscript{2} level, a possible retrofitting option could exist for an applied co-firing case under air to oxy-fuel condition. As discussed earlier in Ref. [128], total heat transfer is comparatively low in the case of OF25 and OF30 using biomass as a fuel compared with only coal. Therefore, in order to achieve a similar type of heat transfer performance
for oxy-biomass combustion scenario, an increase in O₂ mass fraction above 30% could be used.

**Figure 2.17:** Prediction of Heat transfer (MW) for coal and biomass firing under (a). OF25 and (b). OF30 cases compared against air–firing adapted from [128].
Table 2.8: Comparison of experimental unburned carbon-in-ash (CIA) measurement during co-firing

<table>
<thead>
<tr>
<th>Cases</th>
<th>0% biomass</th>
<th>20% biomass</th>
<th>40% biomass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CIA\textsubscript{Expt}, % [205]</td>
<td>CIA\textsubscript{Expt}, % [205]</td>
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</tr>
<tr>
<td>Air</td>
<td>2.10</td>
<td>0.70</td>
<td>0.50</td>
</tr>
<tr>
<td>RR75</td>
<td>0.50</td>
<td>0.50</td>
<td>-</td>
</tr>
<tr>
<td>RR72</td>
<td>0.90</td>
<td>0.40</td>
<td>0.25</td>
</tr>
<tr>
<td>RR68</td>
<td>-</td>
<td>0.35</td>
<td>0.15</td>
</tr>
</tbody>
</table>

2.9.8. Effect of Ash Quality and Burnout

CFD ash deposition modelling is utilized in several studies for determination of ash deposition in pulverized co-firing biomass burner. Losudro [236] presented a three dimensional CFD study for determining the ash deposition characteristics validated with the experimental data performed on a bench-scale combustion facility. Another study highlighted the differences of two mixing methods of biomass and coal and their drawbacks are estimated using CFD modelling [31]. In another study, mixing of flue gases in co-firing has been studied numerically in Ref. [37]. Advanced CFD models demonstrated the effect of ash deposition characteristics. The impact of such behaviour during co-firing can be important.

To decrease the quantity of carbon not burned properly due to incomplete combustion as well as to upgrade the plant efficiency, prediction of unburned carbon in ash is important. Recent experimental studies highlighted this phenomenon and a similar trend was found in the predicted values compared to experimental work. These studies compared the unburned carbon in ash data predicted in CFD studies with the available experimental result. The measured value of unburned carbon in a co-firing study is presented in Table 2.8 for different combustion cases. Better burnout under oxy-fuel firing cases was found compared with air combustion for different biomass sharing cases (20% and 40% biomass-by mass basis). It was seen that when biomass sharing is
increased, carbon amount is decreased in all cases. It was concluded that amount of unburned carbon depends on several factors such as particle size and shape, combustion conditions and residence time. The decrease of overall unburned content for increased biomass sharing is not only due to improved combustion conditions which favour coal particles but also the contribution of both fuels to the favourable result.

2.10. Slagging Modelling Concept

2.10.1. Modelling of Slagging

In general, the modelling of slagging consists of several complex and simultaneous processes, such as the slag flow, particle capture and particle consumption modelling. An understanding of the fundamentals in modelling of slagging is important. A graphical representation of the process involved in slag formation is given in Figure 2.19. When the fuel particle hits the wall of the furnace, some of the particles are captured and some of the particles are rebound from the wall. The captured particles are passing through wall burning process [237]. A basic schematic illustration of the slag formation on a typical refractory wall and membrane wall are presented in Figure 2.20. This figure illustrates the fundamentals of slag layer formation and associated mass and heat transfer processes. When molten ash particles hit the refractory wall, based on the capturing criteria, they are captured and deposited on the wall. Due to particle motion and the gravity effect, this newly formed molten slag layer is driven in the downwards direction. If the operating temperature is below the ash fusion temperature, a solid slag layer may be formed in between the molten slag layer and the wall. When the molten slag starts to solidify, its temperature is gradually decreased.
2.10.2. Molten Slag Flow Model

The slag flow model developed by Yong work based on an Eulerian-Lagrangian approach can be described by the mass, momentum and energy conservation equation as [237, 238]. In modelling of slag layer in solid fuel gasification process in [238], the significant assumptions were considered, as lower slag thickness, unidirectional flow, shear stress due to captured particles and slag properties are calculated at slag mean temperature. For the slag flow, Chen [56, 239] describes the 3D modelling that includes discrete phase and volume of fluid model for the modelling of slag layer in horizontal and vertical furnace respectively.

![Image](image.png)

(a). Horizontal wall [237]  
(b). Vertical wall

Figure 2.18: Main process involved in slagging combustion.
Figure 2.19: Fundamentals of the slagging on the wall in gasifier [240].

(a). refractory wall

(b). membrane wall
Table 2.9: Char capturing criteria used in [239].

<table>
<thead>
<tr>
<th>Wall</th>
<th>Particle temperature, $T_p &gt;$ Critical temperature, $T_{cv}$</th>
<th>Particle temperature, $T_p &lt;$ Critical temperature, $T_{cv}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conversion $&gt; C_r$ [241]</td>
<td>Conversion $&lt; C_r$ [241]</td>
</tr>
<tr>
<td></td>
<td>$W_e &gt; W_{ecr}$</td>
<td>$W_e &lt; W_{ecr}$</td>
</tr>
<tr>
<td>$T_{wi} &lt; T_{cv}$</td>
<td>Trap</td>
<td>Trap</td>
</tr>
<tr>
<td>$T_{wi} &lt; T_{cv}$</td>
<td>Reflect</td>
<td>Trap</td>
</tr>
</tbody>
</table>

We>$W_{ecr}$

We<$W_{ecr}$

$W_{ecr}$>$W_{ecr}$

$W_{ecr}$<$W_{ecr}$
Figure 2.20: Parameters used in the integrated slag flow models [242].

As input conditions for the slag model, the heat fluxes, slag mass flow rates and gas temperatures can be integrated from the coupled CFD code. Seggiani [242], in his 1D modelling, illustrates an input-output variables scheme of the slag model coupled with 3D CFD code as shown in Figure 2.21.

2.10.3. Char Capture Modelling

In the combustion process, fuel particles are always at the state of melting. It is very difficult for them to drive back to spatial space. Particles having greater size try to be carried into the gaseous field again after depositing. In coal-fired boilers, the size of most particles is >1 mm, so most of the particles cannot go back to flow space. When these char/ash particles hit the furnace wall, most of the particles are captured on the wall and some particles rebound from the wall. Determining the capturing/rebounding criteria is important in modelling the slagging in CFD. Several authors used particle capture sub model to define particle capturing criteria to form slag or not on the refractory wall. Chen [56, 239] developed the particle capture criterion considering three major
parameters; the temperature of the particle, temperature of the combustor wall and the carbon conversion of the particle. Based on the assumptions documented in Refs. [241, 243], when both the walls and the particles are sticky, the ash/char particle will be captured. If the wall is not sticky, there is still a possibility for particle trapping. This is determined by the Webber number which is defined as the ratio of particle kinetic energy to the surface tension energy [243]. The critical value of Webber number is assumed as 1.0 [244]. When the Webber number crosses the critical value, the particle will rebound. Based on the stickiness and the Weber number of the particles, the char capture criteria is summarized in [239] as shown in Table 2.9. Though a number of capturing criteria have been developed, a comprehensive modelling for the ash particle capture is required.

![Diagram of particle burning in slagging combustor](image)

**Figure 2.21:** Diagram of particle burning in slagging combustor [245].
2.10.4. Wall Burning Sub-models

In the slagging furnace, the process of free flow particle combustion, its depositions (trapping/rebounding) and wall burning are simultaneous process. These processes are interrelated and relate to each other in terms of physical parameters like viscosity and temperature. The burning characteristics of particles on the molten slag layer with the associated process are presented in Figures 2.22-2.23. Fundamentals about the wall burning process are given in [245, 246]. After a char/ash particle is trapped on the refractory wall, passes through the wall burning process starts. After sticking on the wall, the molten slag moves in the flow direction. Wall burning is a slower char combustion process because of the slower diffusion of oxygen on the particles external surface. Considering the slower reaction of submerged particles in the wall slag layer, a wall burning sub model is proposed in [56, 237-239] which considers the sink position of the trapped particles.

**Figure 2.22:** Diagram of molten slag burning in wall [245].
2.10.5. Effects of Slag Properties

Determination of slag properties such as viscosity, density, specific heat and thermal conductivity are dependent on ash composition, availability of oxygen and temperature [238]. The chemical compositions of the slag vary due to variation of coal slag origination. The slag mineral composition is usually measured by the use of X-ray fluorescence (XRF) method. The temperature of critical viscosity is the most important property for slag modelling. The temperature of critical viscosity is a property which is challenging to predict as it defines the liquid and solid slag layers interface. Due to lack of data from the experimental studies on the ash properties, properties are often predicted based on correlations. The value of temperature at critical viscosity is suggested as 1680K in the correlations [242]. Determination of wall emissivity is another important factor. In the study of Ref [247], the slag emissivity having value of 0.83 were shown over the temperature range.
### Table 2.10: Summary of the modeling attempts for slagging

<table>
<thead>
<tr>
<th>Simulated object</th>
<th>Modelling approach</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prenflo gasifier</td>
<td>This model provides the slag deposit thickness, the temperature across the deposit and heat flux to the metal wall. But this model cannot resolve the slag behaviour in the azimuthal direction.</td>
<td>[242]</td>
</tr>
<tr>
<td>IGCC power plant</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel: Coal &amp; Lime stone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Code: WBSFPCC2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pilot scale combustor</td>
<td>This model demonstrates the deposition and burning characteristics during slagging co-firing, especially the wall burning mechanisms.</td>
<td>[245]</td>
</tr>
<tr>
<td>Fuel: Coal &amp; wood</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Code: WBSFPCC2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pilot scale combustor</td>
<td>This model considers wall burning sub process when particle are trapped on slag layer and its effects on the boiler wall performance. This model considers only molten slag thickness; no solid layer thickness is solved.</td>
<td>[246]</td>
</tr>
<tr>
<td>Fuel: Coal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Code: WBSFPCC2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Entrained flow gasifier</td>
<td>Developed a multiphase multilayer phase transformation model. The viscosity-temperature relationship in the slag is established.</td>
<td>[240]</td>
</tr>
<tr>
<td>Fuel: Chinese, Beisu and Boadian coal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Code: FLUENT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5MWth ITEA Spa &amp; ENEL combustor</td>
<td>The accumulated molten slag is 1-2 mm having average slag velocity of 0.1mm/s due to high viscosity</td>
<td>[56]</td>
</tr>
<tr>
<td>Fuel: Bituminous coal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Code: FLUENT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5MWth ITEA Spa &amp; ENEL combustor</td>
<td>Ash capturing ratio decreases with the increase of temperature of critical viscosity.</td>
<td>[239]</td>
</tr>
<tr>
<td>Fuel: Bituminous coal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Code: FLUENT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test Facility</td>
<td>Test Material</td>
<td>Test Method</td>
</tr>
<tr>
<td>--------------</td>
<td>---------------</td>
<td>-------------</td>
</tr>
<tr>
<td>5MWth ITEA Spa &amp; ENEL combustor</td>
<td>Bituminous coal</td>
<td>FLUENT</td>
</tr>
<tr>
<td>IGCC Power plant combustor</td>
<td>Coal, petcoke, waste</td>
<td>GLACIER</td>
</tr>
<tr>
<td>High purity alumina reactor (T=1350°C)</td>
<td>SS001 coal, Funao-Sekiyama limestone</td>
<td>FLUENT</td>
</tr>
<tr>
<td>A lab-scale LEFR</td>
<td>Illinois 6 coal</td>
<td>FLUENT</td>
</tr>
<tr>
<td>Entrained-flow gasifier</td>
<td>Wyoming and Oklahoma coal</td>
<td>PCGC-2</td>
</tr>
<tr>
<td>FPTF at ABB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>512-MW boiler at EERC's coal</td>
<td>AshProSM</td>
<td></td>
</tr>
</tbody>
</table>
2.11. Recent Numerical Activities on Slagging

In recent years emphasis has been given to the furnace slagging problem as it is considered to be a threat to the long term performance of the boiler. Many efforts have been given to identify the problems and related issues to avoid these problems experimentally. Several numerical studies were also carried out to investigate the fundamentals and detailed associated phenomenon in these problems. Table 2.10 shows the summarized endeavours in modelling the formation of slag by the researchers. Li [243, 251] conducted an experimental study to determine the physical phenomena associated with char–slag transition in an entrained-flow reactor. The physical properties of the char and slag particles were characterized, including the particle density, size, internal surface area and morphology. The major phenomena which indicate the char–slag transition are density increase, size reduction and surface area decrease. Predicted results showed that the particle capture efficiency was a function of coal conversion.

Seggiani [242] developed a simplified model for the simulation of time varying slag flow in a Prenflo entrained flow reactor of the IGCC Power plant, Spain. The furnace was operated at 25 bar supplied with coal and limestone mixtures as fuel. In modelling the slag formation, physical properties such as critical viscosity, specific heat, thermal conductivity are taken in to account. In this modelling, the gasifier’s wall was divided into 15 cells. This one dimensional slag building model can be described by the mass, momentum and energy quantity equation written for each control volume considering Reid and Cohen model assumptions [252]. This model is integrated with a 3D code to obtain mass deposition rate, gas temperature and heat flux. Figure 2.21 shows the implemented input–output variables scheme of the integrated models used in
that code. The deposited slag thickness, temperature and heat flux were determined by using this model. Temperature of critical viscosity is considered as an important parameter which is dependent on the composition of slag.

Wang [245, 246] developed a 1D steady state model to determine the deposition and burning characteristics during slagging co-firing of coal and wood. In this model, particle deposition, wall burning and slag flow are considered. Particle impingement and particle sticking characteristics are applied by using Wood’s [253] and Walsh’s [254] mechanisms. Particle stickiness dependent on critical temperature of ash particle which can be expressed in terms of slag softening temperature. The importance of this model is the inclusion of wall burning and slag flow process, but only limited for molten slag modelling. Compared to Seggiani’s model [242], the Wang model [245, 246] reflects the wall burning phenomenon when fuel particles are stuck on the slag surface and its consequence on char oxidation and heat transfer performance. However both of the models cannot determine the slag behaviour in others direction.

Yong [237, 238] developed a steady state model to describe the flow and heat transfer characteristics in slag layer of solid fuel gasification by combining the model developed by Seggiani [242] and Wang [245, 246]. In this modelling an updated temperature profile is assumed replacing Seggiani’s assumptions. The model considers slag flow characteristics, particle capture and wall consumption. Slag layer does not significantly affect wall temperature and heat flux.

Bockelie et al. [255] and Chen et al. [239] extended the 1D slag model into the 2D wall surface in fuel combustor where slag flow is considered in one direction only. This 2D method considers the spatial distribution of ash particle deposition. This approach cannot completely solve the 3D flow behaviour. Liu
and Hao [256] modelled a two dimensional slag flow in an entrained flow gasifiers using the Volume-of-Fluid (VOF) model. Ni et al. [240] used the same technique to model the multiphase multilayer slag flow and phase transformation considering two-dimensional mesh with uniform ash deposition rate. Chen [56] developed a comprehensive 3D slag flow model to determine the slag behaviour during coal combustion and gasification in a 5MW pressurized coal water slurry (CWS) vertically oriented oxy-fuel furnace. The model couples Volume of Fluid and Discrete Phase Model implemented in a commercial CFD code FLUENT using a detailed particle capture and wall burning sub model written and integrated with the CFD framework. This model fully resolves the three-dimensional characteristics of char/ash deposition, slag flow, as well as heat transfer through the slag layer. It was observed that molten ash properties are critical to the slag layer build up.

Chen [56] developed a comprehensive three dimensional slag flow model to determine the slag behaviour during coal combustion and gasification in a 5MW pressurized coal water slurry (CWS) vertically oriented oxy-fuel furnace. The model integrated different models for fluid and particle trajectories modelling implemented in a commercial CFD code FLUENT using a detailed particle capture and wall burning sub model written and integrated with the CFD framework. The VOF model was used for slag flow modelling and the Discrete Phase Model (DPM) was used for fuel particle trajectories modelling. This model completely decides the 3D features of char/ash deposition, slag flow, as well as heat transfer through the slag layer. It was found that the effect of temperature at critical viscosity and viscosity of slag formed are important in the process of slagging (both molten and solid slag). The proportion of ash captured on the cylindrical wall decreases when temperature at critical viscosity increases. The slag thickness, velocity, and heat transfer were predicted for both the furnaces.
Figure 2.23: 3D simulated results in a 5MW combustion test facility [56].

Figure 2.24 shows the visualization of the molten slag thickness, slag surface flow velocity, slag volume fraction near the wall respectively based on Chen [56]. The result showed that 1–2 mm slag layer is formed on the refractory wall which is basically molten. This molten slag runs downward on the refractory wall, gathers on the floor of the furnace and exits at the lower wall of the combustor, mostly driven by gravity for the horizontal furnace. The mean slag flow rate is normally about 0.1 mm/s. Overall, this three dimensional model is general enough to predict the coal slagging gasification and burning of coal with other combustor designs.
In all the furnaces, near the inlet region, both the velocity and slag thickness are very small for comparatively low temperature. When the temperature exceeds the melting point temperature, slag appears. The relationship between the slag thickness and slag velocity, heat flux and slag temperature are presented in Figures 2.25-2.27 based on the numerical work of Wang [245]. It is observed that slag velocity decreases with the increase of slag thickness. Similar trends is observed in the study of Chen [56].
Recently, Taha [257] conducted a computational modelling to investigate the deposition behaviour of meat and bone meal (MBM) co-firing with coal in the Maasvlakte boiler. A series of co-firing ratios were predicted considering 0%, 12.5%, 25% and 40% of MBM. It was shown that deposition propensity is maximum for 25% case. Recently, Bi [258] developed a combined slag flow model for entrained flow gasification by combining Wu [259] and Seggaini [242] models. In this study, a capturing criteria was developed based on the experimental study of Li [260] and particle behaviour was predicted according to particle size with the slag thickness sensitivity analysis. The structure of the developed slag model is shown in Figure 2.28.

![Figure 2.25: Heat flux distribution through the slag layer and refractory wall along the axial distance [245].](image)
Figure 2.26: Temperature distributions in the slag layer as a function of axial distance [245].

Figure 2.27: A typical structure of slag formation modelling [260].

Overview: In this chapter, an investigation on the radiative and convective heat transfer performance of the combustion of pulverised Russian coal having higher calorific value in a 0.5MWth combustion test facility (CTF) has been conducted. Different combustion environments were investigated including an air-fired as reference case and three recycled flue gas (RFG) fired combustion environments. The different cases were composed of varying recycled ratio (RR) between 65% to 75%. It was found that the flame temperature distribution for the reference case (air fired) and RR72% case were similar. The flame temperature increased with O\textsubscript{2} concentration and decreasing RR. With the decrease of RR, the length of the flame was also shortened. The ignition condition improved with enriched O\textsubscript{2} concentration in the RR65% (O\textsubscript{2} 30.9 %, CO\textsubscript{2} 69.2 % by mass) case. The results showed that radiative and convective heat flux was significantly manipulated by the RR. With the increase of normalized total flow, mean flame temperature and exit temperature decreased whereas with the increase of normalized O\textsubscript{2} flow, mean flame temperature and exit temperature increased. The working range for the Russian coal, suggested that the air equivalent radiative heat flux could be obtained at a RR of \(\approx71\%\) while an air equivalent flame temperature was observed at RR of 72 %. Reasonable agreement has been obtained for unburned carbon in ash. An improved burnout was observed in RR conditions.
3.1. Introduction

Combustion of fossil fuel is a proven thermo-chemical conversion technology for heat and power production which is connected with formation of pollutant and is also a source of deterioration of the global environment. Coal is a major source of fossil fuel, responsible for generating electrical energy in the world [101]. Also, combustion of coal results in the emission of greenhouse gases, the accumulation of which in the atmosphere since the start of the industrial revolution has been contributing to climate change [102]. In this concern, international efforts, like the Kyoto protocol requested an obligation for the reduction of emissions specially CO$_2$ from industrialized countries. For the reduction of CO$_2$ emissions from coal fired power plants, a number of CO$_2$ capture technologies, can be implemented for continuing use of fossil fuel [21, 102-105] such as post-combustion capture, pre-combustion capture, and oxy-combustion. Apart from these processes, different separation techniques are also suggested as gas phase separation, absorption, adsorption and hybrid processes. Recent developments in the CO$_2$ capture technologies include some innovative concepts (i.e. calcium looping, chemical looping, and amines scrubbing systems) suggested in literature. Calcium looping (CaL), a post combustion capture technology, is suggested as a competitive concept for CO$_2$ reduction technique [106] for power plants. CaL is achieved by oxy-firing for the generation of CO$_2$ rich flue gas which is absorbed by CaO and CaCO$_3$ in carbonator. But this technique is relatively more energy consuming. The ECO-Scrub combustion concept [16], a combination of partial oxy-fuel combustion and post combustion capture, provide comparatively higher efficiency than only post combustion process. Another important concept is chemical looping combustion (CLC) [77, 107-110]. In CLC, high purity and concentrated CO$_2$ stream is produced as there is no contact between the fuel and the air as metal
oxide works as transportation media for \( \text{O}_2 \). Hence, lower energy is required compared to other \( \text{CO}_2 \) separation processes.

Among all the carbon capture technologies, oxy-fuel combustion is a greenhouse gases (GHG) abatement technology in which coal is burned using a mixture of \( \text{O}_2 \) and recycled flue gas (RFG), to obtain a rich stream of \( \text{CO}_2 \) ready for sequestration [22]. This carbon capture technology has been considered as one of the most effective technologies to reduce gaseous emissions. In general, the conventional boiler uses air as an oxidizer in the combustion process, hence nitrogen is the main component in the flue gas as its concentration in the air is approximately 79% by volume. But, in the oxy fuel combustion, air is replaced with oxygen and recycled flue gas mixture. The flue gas produced in oxy fuel combustion has a very high concentration of \( \text{CO}_2 \) compared with the flue gas achieved in the air combustion, and is ready for sequestration. A basic schematic of oxy fuel combustion with the RFG is shown in Figure 3.1. Recycled Ratio (RR) is the most significant parameter in an oxy-fuel system when operated with RFG. It is a function of gas mass flow rate, \( m_{\text{RFG}} \), kg/s, and the product gas mass flow rate, \( m_{\text{PFG}} \), kg/s. Product flue gas (PFG) is the amount of flue gas produced within the furnace due to combustion. As \( \text{CO}_2 \) has a higher specific heat capacity compared with \( \text{N}_2 \), the oxy-fuel combustion flame has different radiative characteristics compared to the air fired flame, so the use of oxy fuel combustion technology leads to many changes in the furnace [16, 23]. The recycled ratio can be defined as follows:

\[
RR = \left( \frac{m_{\text{RFG}}}{m_{\text{RFG}} + m_{\text{PFG}}} \right) \times 100
\]

Equation (3.1)

In recent years, many efforts have been devoted to the development of oxy-fuel technology [18, 23, 102, 111-116]. From pilot-scale and laboratory scale experimental studies, oxy-fuel combustion has been found to differ from air combustion in several ways, including reduced flame temperature, delayed
flame ignition and reduced greenhouse gas (GHG) emissions [102]. Several small scale experimental studies have been conducted [18, 19, 116-125] at various combustor designs. A 20 KW down-fired coal combustor was considered by Liu et al. [117] using the coal in air and in oxy coal environment. Significant differences were observed in the char burnouts and gas temperatures in oxy fuel combustion case. Another study considering an entrained flow reactor was used in [126] to investigate experimentally the ignition and burnout of coals under oxy-fuel conditions. The ignition temperature of the individual coals showed a strong dependence on the composition of the atmosphere. The burnouts of the samples with a mixture of 79% CO$_2$-21% O$_2$ were lower than those conducted in air. When the O$_2$ in the mixtures was increased to a value of 30%, the burnout was higher than in air.

![Figure 3.1: Schematic of a typical RFG fuel combustion system](image)

Suda et al. [119] conducted an experimental study in a chamber considering different kinds of coal particles to investigate the effect of carbon dioxide (CO$_2$). Another experimental study for the firing of dry lignite under O$_2$ enriched environment in a 0.5MW test facility has been conducted by Kaß et al. [121] focusing on the flue gas compositions in air and oxy-fuel combustion condition. Several numerical attempts have been made to computationally model the combustion in oxy fuel environments in recent years [125, 127-129]. Edge [129], in his numerical study, investigated the effect of radiation to the furnace wall by
using large eddy simulation (LES) and Reynolds-averaged Navier–Stokes (RANS) based governing equations. The flame properties were clarified for coal combustion in an air- and oxy-fired combustion test facility (CTF). Recently, Audai et al. [62, 95, 96, 99, 100] carried out comprehensive modelling for the combustion of pulverized dry lignite in both lab scale [95, 96, 99] and large scale [62, 100, 130, 131] furnaces under different combustion environments. The studies demonstrated the flame ignition changes and the ignition stability of coal flame in air and oxy fuel combustion scenarios. The effects of SOx and NOx emission concentration have also been investigated. These numerical results showed that the flame temperature distributions and O\textsubscript{2} consumptions in the oxy fuel case were approximately similar to the air combustion case for 25% O\textsubscript{2} and 75% RFG.

For designing a new or retrofitting an existing boiler for oxy fuel combustion capability, a detailed study of radiative and convective heat transfer is important. The present work is an attempt to model these issues and to address the effects of oxy-fuel firing on radiative and convective heat transfer. The main focus of this work is to determine the effect of recycled ratio (RR) on the flame heat transfer performance. The work entailed CFD modelling of the RWEn combustion test facility (CTF) located in Didcot, UK [205] to determine the effect of oxy fuel combustion of Russian coal burnt in air and in a stream of O\textsubscript{2} diluted with RFG and to predict the emission of CO\textsubscript{2} and the radiative as well as convective heat transfer performance of the furnace. This chapter provides a guideline for designing a new or retrofitting an existing boiler with oxy fuel combustion capability considering heat transfers. The balance between convective and radiative heat transfer will be addressed for operations of the boiler in air and also in oxy-fuel firing conditions. Also, the burnout of the coal particle will be explored in details. Overall, this study endeavours to obtain a comprehensive understanding of the mechanism of oxy-fuel combustion
technique using a finite volume based computational tool, AVL Fire version 2009.2 code coupled with the user defined subroutines.

3.2. A review of Experimental Study of Smart

The 0.5MWth combustion test facility (CTF) used in the study of Smart [205-207], located in Didcot, UK was chosen for the present numerical study of air and recycled flue gas (RFG) combustion cases (as shown in Figure 3.2). This facility is equipped for coal combustion under air and oxy-fuel conditions. [205-207] are the experimental investigations of the effect of Radiative and convective heat transfer and burnout effects of Russian coal and South African coal with different recycled ratios (RR) and the co-combustion of highly volatile coal with 20% Saw dust and 20% Shea Meal under different combustion environment. The recycled ratios (RR) considered in this experimental study were RR65 % (total O₂ 30.9 % and total CO₂ 69.2 % by mass), RR72 % (total O₂ 25.4 % and total CO₂ 74.6 % by mass) and RR75 % (total O₂ 22.8 % and total CO₂ 77.2 % by mass).

![Figure 3.2: RWEn combustion test facility (CTF) located in Didcot, UK [205].](image)
In all the cases, a primary constant air flow of 15 m/s was maintained and the secondary flow was varied with RR. At the exit, 3% excess O$_2$ was maintained for all the cases experiment. Radiative heat flux was measured on the side wall at different location. In measuring the radiative heat flux, a MEDTHERM digital heat flux meter was used. The details of this device is given in [261]. In the present numerical study, only Russian coal was considered for both air firing and oxy-fuel cases of RR75 %, RR72 % and RR65 % firing conditions. The proximate and ultimate analysis of the used coal is given in Table 3.1. A scaled version of international flame research foundation (IFRF) aerodynamically air staged burner (AASB) [262] with primary oxidizer and coal and secondary preheated oxidizer was used and fired at constant thermal input of 0.5 MWt for all conditions. The temperatures were maintained at 70° C and 270 °C at the inlets of primary and secondary respectively. Constant secondary swirling flow was maintained with the swirled number of 0.6 for all the experiments.

**Table 3.1: Proximate and ultimate analysis of the fuel used**

<table>
<thead>
<tr>
<th>Proximate analysis, %wt (ar-as received, daf-dry ash free)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ash content %ar</td>
</tr>
<tr>
<td>Moisture content %ar</td>
</tr>
<tr>
<td>Combustibles %ar</td>
</tr>
<tr>
<td>Volatile matter %daf</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ultimate analysis, %wt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon, C %ar</td>
</tr>
<tr>
<td>Hydrogen, H %ar</td>
</tr>
<tr>
<td>Nitrogen, N %ar</td>
</tr>
<tr>
<td>Sulphur, S %ar</td>
</tr>
<tr>
<td>Oxygen, O %ar</td>
</tr>
<tr>
<td>Heating value, GCV kJ/kg</td>
</tr>
</tbody>
</table>
**Table 3.2:** Chemical reactions considered in this study

*Homogeneous reactions (For Devolatilization process)*

\[ \text{CH}_4 + \text{O}_2 \rightarrow \text{CO} + \text{H}_2 + \text{H}_2\text{O} + \text{Heat} \]

\[ \text{CO} + \text{H}_2\text{O} \rightleftharpoons \text{CO}_2 + \text{H}_2 \]

\[ \text{O}_2 + 2\text{H}_2 \rightleftharpoons 2\text{H}_2\text{O} \]

*Heterogeneous reactions (For char oxidation process)*

\[ \text{C}_{\text{char}} + \text{O}_2 \rightarrow \text{CO}_2 + \text{Heat} \]

---

**Table 3.3:** Summary of the model formulation

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Model Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mesh type</td>
<td>650000 cells, symmetric grid</td>
</tr>
<tr>
<td>Spatial discretization</td>
<td>2\textsuperscript{nd} order upwind</td>
</tr>
<tr>
<td>Pressure formulation</td>
<td>SIMPLE</td>
</tr>
<tr>
<td>Gas phase model</td>
<td>Eulerian partial differential equations</td>
</tr>
<tr>
<td>Particulate phase model</td>
<td>Discrete Droplet Method (DDM)</td>
</tr>
<tr>
<td>Devolatilization</td>
<td>Single reaction model</td>
</tr>
<tr>
<td>Char combustion</td>
<td>Global power-law</td>
</tr>
<tr>
<td>Turbulence</td>
<td>The k–(\varepsilon) turbulent model</td>
</tr>
<tr>
<td>Radiation</td>
<td>Discrete transfer radiation method (DTRM)</td>
</tr>
</tbody>
</table>

---

### 3.3. Mathematical Models

It is important to be able to accurately calculate and predict the temperature levels, turbulent flow fields, species concentrations, and emission levels from combustion equipment, especially with the present concerns about greenhouse gas (GHG) emissions. In this study, a three dimensional computational fluid dynamics (CFD) simulation of coal combustion under different operating conditions was carried out by a commercial CFD, AVL Fire version.2009.2 code to analyse the computational domain system that included chemical reaction,
radiative heat transfer, fluid flow field, and turbulent models etc. In this numerical simulation, a Eulerian/Lagrangian approach was employed for gas–solid two-phase fluid flow. This code is useful for solving fluid and particle flow and turbulence, convective and radiative heat transfer. In order to solve the chemical reactions such as devolatilization and char burnout, appropriate subroutines were written and coupled with the code. As combustion consists of complex carbon-oxygen reactions, devolatilization and char oxidation are expressed in the form of homogeneous and heterogeneous reactions. The suitability of multi-steps chemical reactions (one step, two steps and three steps) was conducted by one of the authors [95]. Following Ref. [95], three steps chemical reactions were considered for the process of devolatilization. As char oxidation is mainly governed by the diffusion of $O_2$, global reaction of order unity is considered in this study as suggested by [95-97]. The limitations of the global power law is its dependence on temperature and oxygen partial pressure to the order of char reaction rate and $CO/CO_2$ production rate as described by Hurt and Calo [98]. Therefore, a three steps oxidation model for a complex combustion environment is described in [16, 98]. In this study, the burning of coal particles or its consumption was assumed as the combined hydrocarbon volatile gas burning and char residual oxidation in accordance with Abbas [62, 95, 96, 99, 100]. As there was no critical differences between methane and product from devolatilization of coal used, all the hydrocarbon (HC) gas was considered as methane equivalent as suggested by [79]. Homogeneous and heterogeneous chemical reactions are given in Table 3.2. To illustrate the applications of combustion modelling in CFD, it is important to define all the mathematical models that relate to this combustion phenomenon. The details of the model are described below and a summary is given in Table 3.3.
3.3.1. *Gas Phase Model*

In gas phase modelling, 3D non-steady state Eulerian partial differential conservation equations (PDEs) are considered for multi-component gaseous phase. The general form of Eulerian transport equation used in the present computation is [263]:

\[
\frac{\partial}{\partial t}(\rho \phi) + \frac{\partial}{\partial x_i}(\rho U_i \phi) = \frac{\partial}{\partial x_i}(\Gamma_i \frac{\partial \phi}{\partial x_i}) + S_\phi + S_{p\phi}
\]  
Equation (3.2)

3.3.2. *Particulate Phase Model*

In the particulate Phase model, a discrete droplet method (DDM) [264] is considered. This method includes the momentum exchange, heat and mass transfer phenomena. The differential equation for a solid particle is defined as follows where the coefficient are given in [219]:

\[
m_p \frac{du_{id}}{dt} = \vec{F}_{idr} + \vec{F}_{ig} + \vec{F}_{react}
\]  
Equation (3.3)

Where, \( \vec{F}_{idr} = \frac{1}{2} \cdot \rho_g \cdot A_p \cdot C_D \cdot |u_{rel}| \cdot u_{rel} \)  
Equation (3.4)

\[
\vec{F}_{ig} = V_p \cdot (\rho_p - \rho_g) \cdot g_i
\]  
Equation (3.5)

\[
\vec{F}_{react} = V_p \cdot \left( \frac{-m_{sp}}{dt} \right)
\]  
Equation (3.6)

3.3.3. *Coal Combustion Models*

Coal combustion modelling composed of several complex physical and chemical processes including gas phase and particle phase modelling. The following three steps considered for coal combustion: 1. thermal decomposition, 2. burnout of the volatile matter and 3. oxidation of char.

3.3.3.1. *Coal Combustion Gas Phase*

The Eddy Breakup (EBU) model is one of the important turbulence controlled combustion models. This model was first introduced by Spalding [265] and
modified later by Magnussen and Hjertager [266]. This model determines whether, O₂ and fuel are in limiting condition and the reaction possibility. In this model, the mean reaction rate is an important parameter which is defined as [266]:

$$\bar{r}_{fu} = \frac{C_{fu}}{\tau_R} \bar{\rho} \min \left( \frac{y_{ox}}{S}, \frac{C_{pr} y_{pr}}{1+S} \right)$$  \hspace{1cm} \text{Equation (3.7)}

The effect of turbulence in the coal combustion gas phase is explained by Molemaker and VilÅ-Guerau de Arellano [267]. In this phase, if, \( y_v = \) volatile mass fraction, \( y_{ox} = \) oxidant mass fraction, \( y_c = \) char mass fraction, then the mass fraction of product \( y_{pr} \) can be calculated as:

$$y_{pr} = 1 - y_v - y_{ox} - y_c$$  \hspace{1cm} \text{Equation (3.8)}

| Table 3.4: Kinetics Parameters for the particle combustion modelling |
|-------------------------------|-----------------|-----------------|
| **Kinetics parameters** | **Pre-exponential factor, \( A_c \)** | **Activation energy, \( E_c \)** |
| Devolatilization | \( 4.2 \times 10^{14} \text{ s}^{-1} \) | \( 230 \) (kJ mol⁻¹) |
| Char oxidation | \( 497(\text{kgm}^{2}\text{s}^{-1}\text{Nm}^{-2})^{-1} \) | \( 155 \) (kJ mol⁻¹) |

### 3.3.3.2. Coal Combustion Particle Phase

Two very important terms in the modelling of coal combustion are devolatilization and char oxidation. These processes are complex and the kinetics parameters in these models are given in Table 3.4.

#### 3.3.3.2.1. Devolatilization

In fuel pyrolysis simulation, the single reaction model proposed by Badzioch and Hawksley [268] was considered. The volatile production rate is defined as:

$$\frac{dV}{dt} = K_v(V_f - V)$$  \hspace{1cm} \text{Equation (3.9)}

The rate constant, \( K_v \) can be defined by the Arrhenius form as:
\[ K_v = A_v \exp \left( \frac{-E_v}{T_p} \right) \]  
\text{Equation (3.10)}

### 3.3.3.2.2. Char Oxidation

In this study, the char combustion is modelled with a global power-law [27]. Char oxidation is the secondary phase of particle combustion after the devolatilization. When the devolatilization is completed, the remaining amount is char and ash. This char will react with the gases steadily [269]. In this model, diffusion of \( O_2 \) is responsible for the oxidation rate of char particle. This is treated as suitable model compared to any other models [97]. The diffusion rate of oxygen equals to \( K_d (P_g - P_s) \), where \( K_d \) can be defined as:

\[ K_d = \frac{2.53 \times 10^{-7} R_p}{P} \left( \frac{T_p + T_g}{2} \right)^{0.75} P_{\lambda} \]  
\text{Equation (3.11)}

Again, the rate of char oxidation per unit area is \( K_c P_s \), where the value of \( K_c \) can be written as:

\[ K_c = A_c \exp \left( \frac{-E_c}{T_p} \right) \]  
\text{Equation (3.12)}

Finally, the rate of the overall char reaction of a particle can also be written as:

\[ \left( \frac{1}{K_d^{-1} + K_c^{-1}} \right) P_g 4\pi R_p ^2 \frac{P}{P_{\lambda}} \]  
\text{Equation (3.13)}

### 3.3.4. Turbulence Model

The \( k-\varepsilon \) [270] is a commonly accepted model for turbulence modelling, especially for industrial applications and is available in most CFD codes.

Turbulent kinetic transport equations:

\[ \rho \frac{\partial k}{\partial t} + \rho U_j \frac{\partial k}{\partial X_j} = P + G - \varepsilon + \frac{\partial}{\partial X_j} \left( \mu + \frac{\mu_t}{\sigma_k} \frac{\partial k}{\partial X_j} \right) \]  
\text{Equation (3.14)}

Rate of dissipation of energy from the turbulent flow:
\[
\rho \frac{\partial \varepsilon}{\partial t} = \left( C_{\varepsilon 1} P + C_{\varepsilon 3} G + C_{\varepsilon 4} k \frac{\partial U_k}{\partial X_k} - C_{\varepsilon 2} \varepsilon \right) \frac{\varepsilon}{k} + \frac{\partial}{\partial X_j} \left( \mu_t \frac{\partial \varepsilon}{\partial X_j} \right) \quad \text{Equation (3.15)}
\]

\[
P = -2 \mu_t S : S - \frac{2}{3} [\mu_t (\text{tr}S) + k](\text{tr}S), \quad G = -\frac{\mu_t}{\rho \sigma_{\rho}} \nabla \rho, \quad \mu_t = C_{\mu} \rho \frac{k^2}{\varepsilon} \quad \text{Equation (3.16)}
\]

### 3.3.5. Heat Transfer Models

#### 3.3.5.1. Radiative Heat Transfer

Radiative heat transfer is an important phenomenon in combustion modelling, considering emission [271]. Most of the proposed models for radiative heat transfer modelling fall under the category of weighted-sum-of-gray-gases (WSGG) models [203]. The radiative heat transfer modelling is achieved considering the discrete transfer radiation method (DTRM) [272]. In DTRM, radiation transfer equation (RTE) is solved for the calculation of radiation phenomena. In this method, the radiation intensities is defined assuming single ray with constant temperature where the emissivity totally depends upon the local temperature and gases composition [273]:

\[
i'_{n+1} = i'_{n} \left( 1 - \varepsilon(T, x_i) \right) + i'_{b}(T) \varepsilon(T, x_i) \quad \text{Equation (3.17)}
\]

In equation (3.17), the blackbody emissivity is dependent on the gas temperature and the Stephan–Boltzmann constant equals to 5.67 10^{-8} \text{W/m}^2 \text{K}^4. The absorption model selected in this study is of great importance for the radiation calculation, particularly in the RFG combustion because of the higher percentage of concentration of CO₂ [129]. The gas mixture emissivity can be represented through the WSGGM as given in the following equation:

\[
\varepsilon(T, x_i) = \sum_{i=1}^{i+1} \alpha_{\varepsilon_i}(T)(1 - e^{-\alpha_i p + B T_c})
\]

\[
\text{Equation (3.18)}
\]

The weighting factors are usually given by polynoms of order in the following form:
\[ \alpha_{\varepsilon,i}(T) = \sum_{j=1}^{l} b_{\varepsilon,i,j} T^{j-1} \]  
\text{Equation (3.19)}

Accurate selection of the absorption coefficient (for air- 0.24 m\(^{-1}\), for oxy-0.31m\(^{-1}\)), surface discretisation (number of azimuthal division set to 8) and angular discretisation (number of polar division set to 2.0) is important for correct evaluation of the radiation characteristics [96, 274]. More detailed information for the radiation modelling is given in [62, 95, 96, 99, 100].

### 3.3.5.2. Heat and Mass Transfer

In modelling coal combustion, convection and radiation heat transfer are counted during the particle and gas interaction in the furnace. The convective heat transfer is defined as:

\[ Q_c = \pi D_p \lambda N_u (T_g - T_p) \]  
\text{Equation (3.20)}

In this type of heat transfer, Nusselt number, Nu is correlated as [275]:

\[ N_u = 2 + 0.6 Re_p^{0.5} Pr^{0.33} \]  
\text{Equation (3.21)}

The radiative heat transfer between the particle and gas is given by the following equation:

\[ Q_r = \varepsilon \sigma \pi D_p^2 (T_g^4 - T_p^4) \]  
\text{Equation (3.22)}

### 3.3.6. Swirl Number

The swirl number [276] definition is needed for the modelling of the swirled motion of secondary air at the inlet. The definition used in this work is one taken from [277], and it is a modified version [276]. Considering the used burner configuration, it looks like the following in simplified form:

\[ S = \frac{G_{d\phi}}{R.G_x} = \frac{2\pi \int_{R_1}^{R_2} \rho U.W(r)r^2dr}{2\pi.R \int_{R_1}^{R_2} \rho U^2 r.dr} \]  
\text{Equation (3.23)}
\[ S = \frac{\omega}{R.U} \int_{R_1}^{R_2} r^{-3} \, dr \quad \text{Equation (3.24)} \]

\[ S = \frac{R_1^{-2} + R_2^{-2}}{R_1 + R_2} \cdot \frac{\omega}{U} \quad \text{Equation (3.25)} \]

### 3.4. Computational Methodology

#### 3.4.1. Computational Domain

The details of the horizontal furnace geometry as given in [205-207] are shown in Figure 3.3. It consists of a 0.8 m square ceramic lined furnace approximately 4 m long followed by a convergent section leading to a simulated economiser region. A scaled version of an IFRF aerodynamically air staged burner (AASB) was used and fired at a constant thermal input of 0.5 MWt for all tests [129] as shown in Figure 3.4.

*Figure 3.3: Schematic of Combustion test facility (All dimensions in mm)*
**Figure 3.4:** An IFRF aerodynamically air staged burner (AASB) Specification. (all dimensions in mm)

**Table 3.5:** The inlet boundary condition for different combustion cases

<table>
<thead>
<tr>
<th>Flow parameters</th>
<th>Units</th>
<th>Case-I Air firing</th>
<th>Case-II RR75</th>
<th>Case-III RR72</th>
<th>Case-IV RR65</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Primary flow</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass flow</td>
<td>kg/h</td>
<td>110</td>
<td>155</td>
<td>155</td>
<td>155</td>
</tr>
<tr>
<td>Temperature</td>
<td>K</td>
<td>343</td>
<td>343</td>
<td>343</td>
<td>343</td>
</tr>
<tr>
<td>O₂ concentration</td>
<td>(kg/kg)</td>
<td>23.15</td>
<td>16.2</td>
<td>16.2</td>
<td>16.2</td>
</tr>
<tr>
<td>Coal supply</td>
<td>kg/h</td>
<td>68</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Secondary flow</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass flow</td>
<td>kg/h</td>
<td>620</td>
<td>600</td>
<td>512</td>
<td>368</td>
</tr>
<tr>
<td>Temperature</td>
<td>K</td>
<td>543</td>
<td>543</td>
<td>543</td>
<td>543</td>
</tr>
<tr>
<td>O₂ concentration</td>
<td>(kg/kg)</td>
<td>23.15</td>
<td>22.8</td>
<td>25.4</td>
<td>34.8</td>
</tr>
<tr>
<td>Swirl Number</td>
<td>--</td>
<td>0.6</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3.4.2. **Boundary Conditions**

The present computational domain has several boundaries such as inlet boundaries (primary oxidizer, secondary oxidizer, coal supply), wall boundaries and the exit as used in the experiment [205-207] are described as follows.

### 3.4.2.1. **Inlet Boundary Condition**

The inlet boundary includes primary and secondary annular flow through a scaled version of an IFRF burner of the furnace as shown in Figure 3.4. The inlet boundary conditions of the burner, for different combustion cases are given in Table 3.5. Approximately 80% of the total oxidizers enter the secondary and the rest through the primary. The input power of fuel is 0.5MWth and the particle mass flow rate is 68 (kg/h) for all the cases simulated. Swirled flow was generated in the secondary inlet with prescribed angular velocity in relation to the constant swirl number. The primary and the secondary inlet velocity vectors for the air fired case are shown in Figure 3.5. The primary air flow is normal to
the inlet annulus having an area of $1.9 \times 10^{-3} \text{ m}^2$, while the secondary oxidizer is flowing with relatively higher flow rate compared to primary flow through an area of $6.6 \times 10^{-3} \text{ m}^2$.

### 3.4.2.2. Wall Boundary Condition

To be consistent with the experiments [205-207], the wall of the 0.5MWth combustion furnace was divided into several parts: (i). Top wall, (ii). Bottom wall, (iii). Side wall, (iv). Burner quarl wall and (v). Burner end of the combustion furnace as shown in Figure 3.2. Different walls were kept at different thermal resistances of $0.397, 0.235, 0.109, 0.109, 0.109 \text{ m}^2\text{K/W}$ respectively [76]. No-slip boundary condition where $u, v, \text{ and } w = 0$ are assumed and wall emissivity were applied for all the parts. Considering radiative properties of the wall, the assumed value of emissivity is, $e=0.85$ for the furnace wall [278].

![Figure 3.6: The particle size distribution of Russian coal used in experiment and in CFD.](image-url)
3.4.2.3. Outlet Boundary Condition

A zero gradient was applied ($\frac{\partial \phi}{\partial x_i} = 0$) for all variables at the exit of the furnace.

3.4.3. Fuel Analysis and Particle Size Distribution

In the present study, CTF was supplied with Russian pulverized, high volatile bituminous coal as fuel. The coal characterizes with gross calorific value (GCV) of 27,098 KJ/Kg. The proximate and ultimate analysis of coal is summarized in Table 3.1. The fuel particle distribution of Smart [205] is inserted into the computational domain as a Rosin Rammler distribution (RRD) [100]. The
particle size range of Smart [205] was 75-300 μm. The particles distribution profile is presented in Figure 3.6. The characteristics parameters of Rosin Rammler distribution applied in this study are as follows: max particle size, \( d_{\text{max}} = 300 \) μm, min particle size \( d_{\text{min}} = 75 \) μm, RRD mean size, \( d_{\text{RRD, mean}} = 100 \) μm and RRD spread, \( n = 5.78 \). According to Smart [205], approximately 77.5% of the total particle flow had the diameter of 75μm.

### 3.4.4. Numerical Descriptions

In this work, three dimensional governing equations are solved using the commercial CFD tool, AVL Fire ver.2009.2. In this finite volume technique, the semi implicit method for pressure linked equation (SIMPLE) algorithm was used. In case of convergence, value of \( 10^{-4} \) for absolute residuals is considered for all the variables. In order to be consistent with the experiment, i.e. initial start-up of the furnace is achieved by the combustion of the gas only until the flow parameters reached a quasi-steady state. Then, particles were introduced into the furnace. The number of particles per second is set to 10,000 for all the cases considered in this study. A time-step of 0.0025 (s) was used for both gas and the particle trajectories. Flames were stable after 20,000 time steps in all the cases. Finally the numerical results were averaged over the period of 25,000 to 40,000 time-steps. The differencing scheme considered in this study for momentum, continuity, turbulence, energy and scalar had blending factor between central differencing and upwind scheme. For solving continuity equation, central differencing approximation scheme with second order accuracy is considered. The maximum blending factor used in this study was 0.5.
3.4.5. Grid Sensitivity Analysis

As the accuracy of the numerical results depend on the mesh resolutions, a number of trials simulations were carried out with different mesh resolutions to have acceptable accuracy with acceptable computational time. Three different cell sizes with increasing number of elements (500,000, 650,000, and 800,000) were used. Each grid has a similar meshing scheme. A fine mesh is used in the burner region as shown in Figure 3.7. The results from each simulation were compared to evaluate the impact of the grid on the results. The mean values of flame temperature profile, velocity profile, CO$_2$ and O$_2$ concentration profile at the location of 0.3m from the burner end were compared and presented in Figures 3.8-3.11 for the air combustion cases. Average variations of these parameters were compared for the three grid sizes. For the change of grid from 500,000 to 650,000 cells, the average percentage of change for temperature, velocity, CO$_2$ and O$_2$ concentrations were found to be approximately 1.43%, 15%, 1.85% and 9.5% respectively. While for the change of grid from 650,000 to 800,000 cells, the average percentage of change for temperature, velocity, CO$_2$ and O$_2$ concentrations were found to be approximately 0.7%, 11%, 1.2% and 8% respectively. It is seen that the percentage of change is small for all the variables for the change of grid size from 650,000 to 800,000. Therefore, the grid with 650,000 cells was chosen for the current investigation. Also, it was found that the radiative heat flux distribution in the surface wall for the 650,000-grid system matched reasonably well with the experimentally measured values for the air fired case (discussed later).
Figure 3.8: Axial Velocity (m/s) profile in radial direction at 0.3m from burner exit for different Grid sizes.

Figure 3.9: Temperature (K) profile in radial direction at 0.3m from burner exit for different grid size.
**Figure 3.10:** O$_2$ mass fraction (kg/kg) profiles in radial direction at 0.3m burner exit for different grid size.

**Figure 3.11:** CO$_2$ mass fraction (kg/kg) at radial direction profiles at 0.3m burner exit for different grid size.
3.4.6. Code Validation

As mentioned earlier, this computational study simulated the experimental work of Smart [205-207], where radiative heat flux and convective heat flux was measured through the ports in the radiant section of the combustion test facility located in the furnace wall (as shown in Figures 3.3 & 3.7). Published experimental data [205-207] were used to validate the CFD prediction for the selected set of condition involving the combustion of coal in air and further oxy fuel (RR65%, RR72% and RR75%) conditions. As part of the code validation, air combustion modelling of coal with the prescribed boundary condition [205, 206] was carried out and a reasonable comparison was observed when predicted results were compared with the experimentally measured radiative heat flux and the convective heat transfer data. In the experiment it was shown that the measured heat flux for the air combustion was in the range of 270-400W/m². The comparison of the numerical radiative heat flux with the experimental data for air combustion is shown graphically later in result section and detailed explanations of the radiative heat flux and convective heat transfer for different recycled ratios are given in the result and discussion section of this chapter.

3.5. Results and Discussion

Four different combustion environments were investigated in this study. They were: air combustion (23% inlet O₂) (case-I) shown as the reference case, and three different RFG fuel (oxy-fuel) combustion such as case-II-RR75% (22.8 % inlet O₂), case-III-RR72% (25.4 % inlet O₂) and case-IV-RR 65% (30.9 % inlet O₂). The feed gases for these combustion environments are summarised in table 5. In all the combustion cases, some variables were always kept constant such as input power of 0.5 MW, initial conditions (pressure = 101325 Pa, Temperature =
800 K, $\rho = 0.67$ kg/m$^3$). The mass flow rate of coal was also constant for all the air and oxy fuel combustion cases. In the experiments [205-207], for the oxy fuel cases, a dry recycle system was simulated where the O$_2$ concentration in the primary transport was maintained at constant value. Similar condition was maintained in the present numerical analysis.

The change in combustion media from air combustion to the recycle flue gas (RFG) combustion has a significant impact on the characteristics and structure of flame. The details of the different combustion cases are given in Table 3.5. The following section explains the result in details for different combustion cases (Air as the reference case and three RR cases, RR75%, RR 72% and RR65%).

3.5.1. Flame Temperature Distribution

In order to visualize the overall flame temperature, its distributions on the horizontal plane axially along the centre of the furnace are presented in Figure 3.12. It is observed that the flame starts at the burner exit as expected and extended further approximately 1.0 m in the axial direction in the air fired case. The tip of the flame is wider in radial direction as shown in case-I for air combustion. On the other hand, the RFG fired flame for case-IV is more concentrated in the central position compared to the air-fired flame. This variation in the flames shape between air-fired and RFG fuel fired cases can be explained on the basis of the differences in the thermodynamics behaviour between N$_2$ present in air firing and CO$_2$ present in oxy fired cases. The flame temperature for the case of RR72 is very much similar to that of the air-combustion case. But the flame temperature for RR75 is slightly lower than the air fired case. This is due to reduced O$_2$ in RR75 compared to air fired case and availability of CO$_2$ in RR75. The flame temperature of RR72 is higher than RR75, but the length of the flame is smaller and more restricted in the burner exit
region. For the RR65% (total O$_2$ 30.9 % and total CO$_2$ 69.2 % by mass) as shown in case-IV, the flame temperature is higher compared to other two RR cases, but the flame length is lower than air case (case-I) by 15%.

**Figure 3.12:** Flame temperature (K) contour for different cases. (Case-I for air-firing, Case-II for RR75, Case-III for RR72 and Case-IV for RR65)
Figure 3.13: Flame temperature (K) distribution on the radial plane at a position of 0.3 m from the burner exit for four different cases considered.

Figure 3.13 shows that comparatively more luminous flames are seen in case II, III and IV compared to case-I. For the lower recycled ratio of 65%, a much brighter flame is observed compared to the air case. Smart [205, 206] explained this on the basis of possible soot formation in their experimental work. Soot formation is not considered in the present numerical work. The present authors believe that soot formation is not the only reason leading to this brighter flame; one of the other reasons may be lower mass flow rate at low recycled ratio which increases residence time in reaction zone, thus providing better mixing and improved the flame temperature. Also, at lower RR, the flame temperature increases, as the O₂ enrichment level is
comparatively high. Although the specific heat of CO$_2$ is higher, the lower mass flow rate outweighs its effect leading to higher temperature. It is clear that the flame temperature increases when oxygen in the inlet is higher and the recycled flue gas is less. The flame temperature for the case of RR65 is higher compare to RR72 and RR75. The maximum flame temperature for air-fired, RR75, RR72 and RR65 were 2250 K, 2100 K, 2280 K and 2585 K respectively. This phenomenon may be explained on the basis of the characteristics of turbulent time-scale of the Eddy Breakup combustion (EBU) model which suggests a higher flame temperature in RFG environment with O$_2$ enriched cases due to the quick combustion rate [279]. Flame temperature (K) distribution profile along the radial direction at 0.3m from burner end for different cases considered are presented in Figure 3.14.

![Flame temperature (K) distribution profile](image)

**Figure 3.14:** Flame temperature (K) distribution profile along the radial direction at 0.3m from burner end for different cases considered.
3.5.2. Flow Distribution

The velocity vectors at the inlet for case-I is shown in Figure 3.5. For all the other cases, the primary inlet flows were kept constant at a value of 15 m/s, while the secondary flows varied with the variation of recycled ratios (RR), keeping swirl number constant at 0.6. In order to increase the mixing, stabilize the flame shape and to provide enough time to the oxidizers for complete burning of fuel, the swirled flow is used in the burning systems. The swirl effect is significant in the combustion phenomenon. The primary oxidizer and the coal particles are fed into the furnace through primary inlet and swirled secondary oxidizers are fed through secondary air inlet as shown in the burner configuration (Figure 3.4).

![Flow visualization in combustion modelling for reference case (air-firing).](image)

**Figure 3.15:** Flow visualization in combustion modelling for reference case (air-firing).
The flow visualization in combustion modelling for the reference case (case-I) is presented in Figure 3.15. The velocity vectors show internal recirculation zone, reaction zone and external recirculation zone. Although, the aerodynamically air staged burner (AASB) used in the present study is specially configured for proper mixing of the flow, flow condition is also responsible for the generation of recirculation region inside the furnace. The variation in the combustion environment such as composition of the gases, flow rate of the oxidizers affected the flow characteristics and the flow behaviour of the fuel particles. The axial velocity distributions on the axial horizontal plane of the furnace are presented in Figure 3.16. From the figure, it is seen that the velocity of oxidizing gas is decreasing from reference case (case-I) to RR65% case (case-IV). This provides more residence time for the fuel particle to stay in the combustion reaction area and thus better ignition environment which finally improves the flame temperature. The radial velocity profile for selected cases at a position 0.3m from burner end is presented in Figure 3.17.

The fuel particle distribution along with the particle temperature distribution and the particle movement in the furnace for the air combustion case are presented in Figure 3.18 & 3.19 respectively. From the figure it is found that the maximum particle temperature achieved in air combustion is around 2250 K.

### 3.5.3. Species Concentration Distribution

Availability of oxygen (O₂) mass fraction (kg/kg) in the exit of the burner area contributes to the flame characteristics and the ignition environment. The O₂ mass fraction (kg/kg) on a horizontal plane axially along the centre of the furnace is shown in Figure 3.20 for different cases. This figure illustrates the O₂ mass fraction for the air fired and three recycled ratios (RR) cases. It is
seen from the figure that O₂ concentration for air fired case is almost similar to that of RR 75 case. Some delay can be observed in the consumption of oxygen (O₂) in case I and II. For RR 72 (case-III), the profile is more or less similar to RR75% case, but O₂ concentration is slightly higher. But the consumption of O₂ is faster and the availability of O₂ is much enriched in case of RR 65% compared to RR 72% and RR75%, so the ignition condition is improved and better flame is observed just after the exit of the burner.

Figure 3.16: Axial velocity distribution (m/s) for different Cases.
Figure 3.17: Axial velocity (m/s) distribution profile along the radial direction at 0.3m from burner end for different cases considered.

Figure 3.18: Particle temperature distribution at the reaction zone.

Figure 3.19: Particle velocity distribution at the combustion zone.
CO₂ mass fractions are presented in Figure 3.21 displaying the comparisons of the mass fraction distributions (kg/kg) of CO₂ for all the cases. In case of air firing, maximum CO₂ concentration in the furnace is 0.193 by mass (kg/kg). In case of higher RR, CO₂ is much more enriched. But for lower RR65 % case, this fraction goes down to approximately 0.88 by mass. According to chemical properties [280], CO₂ has higher specific heat compared to nitrogen (N₂). This property is responsible for absorbing more heat which will protect the furnace wall and control the overall emissivity.
Figure 3.21: CO₂ mass fraction distribution (kg/kg) for different Cases.

That’s why, increase in CO₂ in RR cases has significant importance in combustion environment compared to air fired case. It is expected that in lower RR with enhanced O₂ level, the effect of CO₂ on the overall emissivity will decrease. When CO₂ in the boiler decreases, the Cp of the flue gas decreases and the temperature can be higher, thus resulting in higher flux. Similar findings have been observed for the species profile at the radial direction. Figures 3.22-26 showed the O₂, CO₂, H₂O, H₂ and HC profile for all the cases respectively.
Figure 3.22: Oxygen (O₂) mass fraction distribution profile along the radial direction at 0.3m from burner end for different cases considered.

Figure 3.23: CO₂ mass fraction (kg/kg) distribution profile along the radial direction at 0.3m from burner end for different cases considered.
Figure 3.24: Water vapour (H₂O) mass fraction distribution profile along the radial direction at 0.3m from burner end for different cases considered.

Figure 3.25: Hydrogen (H₂) mass fraction distribution profile along the radial direction at 0.3m from burner end for different cases considered.
Figure 3.26: Hydrocarbon (CH₄) mass fraction distribution profile along the radial direction at 0.3m from burner end for different cases considered.

3.5.4. Radiative Heat Flux

The CFD predictions of the radiative heat flux for all combustion cases in the radiative sections are shown in Figures 3.27-3.30 against available experimental data [205, 206]. The change radiative heat transfer is linked to the variation in temperature within the furnace. Since the radiation is proportional to the fourth power of the temperature, a correct resolution of the temperature field is important in predicting the radiative heat transfer. The numerical SIRs for the RR75, RR72, and RR65 cases are compared against the experimental case. It is seen from figure that SIR for air combustion is in the range of 250-400 KW/m² whereas for the RR75, RR72 and RR65 cases, a range of 275-340 KW/m², 270-365 KW/m², 340-490 KW/m² respectively. A reasonable agreement can be seen between experimental and numerical results. The variation in SIR with RR can be explained on the basis of O₂ enriched environment. When, the O₂ concentration is increased by
reducing the recycled ratio, the surface incident radiation at the radiative sections increases as the recycled ratio (RR) is reduced from 75% to 65% by volume at the inlet. When CO$_2$ in the boiler decreases, the Cp of the flue gas decreases and the temperature can be higher, thus resulting in higher flux.

The maximum variation between experimental and numerical radiative heat flux for air combustion was 17% while the average difference is around 9%. The maximum differences between the experimental and computational radiative heat flux were: 15%, 12%, and 14% for RR75%, RR 72% and RR65% respectively. But the overall difference is comparatively low. From the figures it can be seen that the average variation is 5.8%, 5 % and 6 % for RR75%, RR72% and RR65% respectively. These variations may be acceptable considering the accuracy of numerical scheme used.

The predicted SIR for RR72 and RR75 are similar to that of air firing case. While for 65% RR, comparatively higher radiative heat flux is observed. This phenomena was also observed in the experimental work of Smart [205]. This results in different flame temperatures as can be seen in Figure 3.16. Temperature increases due to increased combustion rate associated with increased O$_2$ level in lower RR cases. At lower RR, higher O$_2$ concentration provides better mixing of fuel with oxidizer. Also, the lower flow rate provides higher residence time for the fuel in the reaction zone, resulting in increased flame temperature. On the other hand, reduction in RR corresponds to reduction of CO$_2$ amount contributing to the flame emissivity and thus radiative
**Figure 3.27:** The comparison of the numerical radiative heat flux with the experimental data [205] for air combustion case.

**Figure 3.28:** The comparison of the numerical radiative heat flux with the experimental data [205] for RR75% case.
Figure 3.29: The comparison of the numerical radiative heat flux with the experimental data [205] for RR72% case.

Figure 3.30: The comparison of the numerical radiative heat flux with the experimental data [205] for RR65% case.
emission. CO$_2$ has higher heat capacity; hence reduction in CO$_2$ amount will try to keep the flame temperature in the higher range. The results shown in figures indicate that, the position of maximum SIR moves downstream with increasing RR. This can be explained as the effect of increased mass flow rate and reduced O$_2$ at higher RR, shifting the SIR downstream. The increased mass flow rate provides less residence time for the fuel. The reduced O$_2$ provides reduced mixing of fuel and oxidizer.

### 3.5.5. Effects of NTF/NOF/RR on Temperature

Figures 3.31-3.33 show the comparison of the experimentally measured to the numerically calculated mean flame temperature with the RR, NTF and the NOF respectively. The mean flame temperatures are measured at a location just after the burner exit through Port 2 as measured in the experiment [207]. The value of the total flow and O$_2$ flow are normalized with the corresponding values of air firing case as described in [207]. Similar to mean temperature, the furnace exit temperatures are also presented in Figures 3.31-3.33 with respect to RR, normalized total flow and the normalized O$_2$ flow respectively. It is found from the graph (Figure 3.31), mean flame temperature and furnace exit temperature, both decreases with the increase of RR. Higher flame temperature is observed at lower RR. The mean flame temperature decreased by more than 100 K due to change of RR from 65% to 75%. A similar trend is observed for exit furnace temperature. This type of change is due to the difference in CO$_2$ and O$_2$ availability in respective cases. At lower RR, due to higher concentration of O$_2$, combustion rate is comparatively higher, which provides higher mean flame temperature. Also, at Lower RR, CO$_2$ supply is low, which contributes to the increase of mean flame temperature due to its higher heat capacity of CO$_2$. With the increase of NTF, flame temperature and exit temperature decrease (Figure 3.32) whereas with the increase of NOF, flame temperature and exit
temperature increases (Figure 3.33). This can be explained on the basis of residence time and better mixing and availability of O\(_2\) with the fuel. At lower flow, due to higher residence time, faster reaction happens, thus higher flame temperature is observed. While increasing the NTF, provides less reaction time resulting in lower mean flame temperature. But opposite trend is observed for the increase of NOF. As, higher O\(_2\) concentration is responsible for better mixing of fuel with oxidizer resulting in higher flame temperature at higher NOF. Comparing the numerically calculated and experimentally measured mean flame temperatures, the average difference was found to be approximately 20 K.

**Figure 3.31:** Variation of mean flame temperature with the recycle ratio (RR).
Figure 3.32: Variation of the mean flame temperature with the NTF.

Figure 3.33: Variation of the flame temperature with the NOF.
3.5.6. Working Range for New/Retrofitting Purpose

The variation of peak flame temperature for air operation to oxy-fuel operation with different recycled ratios (RR) is presented in Figure 3.34. The figure shows that the peak flame temperature for air operation is equivalent to peak oxy-fuel flame temperature at RR of approximately 72% which is consistent experimental results [205]. The normalized radiative and convective heat fluxes for different RR are presented in Figure 3.35. In case of radiative heat flux, peak values are considered. Convective heat transfer is a single measurement as taken in the experiment [205]. Same procedure as [205] was used in obtaining the convective heat transfer using a specially designed probe. In calculating the normalized radiative heat flux, the values for different RR cases were divided by the value of air firing case. Similar method was followed in calculating the normalized convective heat flux.

Figure 3.34: Oxy-fuel operation to air operation for peak flame temperature with recycled ratio (RR).
The graphical presentation shown in Figure 3.35 can help in evaluating a suitable working range for the coal combustion under varying RR conditions where both radiative and convective heat transfer can be maintained at a unique balance. This information will help in evaluating the performance of a newly build or an existing retrofitted furnace run on both air and oxy fuel combustion. It is seen from the figure that working range of RR may be found for both heat transfer. As expected radiative heat flux decreases with increasing RR. This is due to decreasing flame temperature with increasing RR. But opposite trend is observed in convective heat flux. This is due to increase in the convective heat transfer coefficient and increased mass flow rate with increasing RR. The RR65 case is the one presenting the larger deviations from the air-fired case and it would be best suited for new built plants, while RR72 and RR75 cases could be implemented in existing plants after retrofits. From this plot of heat transfer versus RR, few important ratios for working range can be pointed out for the design or retrofit a typical furnace. Air equivalent radiative heat flux can be observed at a RR of 71% compared to experimental data [205] of 72%. Also the air equivalent flame temperature can be observed at RR of 72 % in this numerical work. The experimental data [205] showed similar values.
Figure 3.35: Oxy-fuel operation normalised to air operation, for peak radiative heat flux, convective heat flux and adiabatic flame temperature.

Table 3.6: Comparison of Carbon-in-ash (CIA, %) measurement

<table>
<thead>
<tr>
<th>Case</th>
<th>Experimental [205], CIA, %</th>
<th>Numerical, CIA, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air firing</td>
<td>2.1</td>
<td>2.45</td>
</tr>
<tr>
<td>RR 75 %</td>
<td>0.5</td>
<td>1.87</td>
</tr>
<tr>
<td>RR 72 %</td>
<td>0.9</td>
<td>1.47</td>
</tr>
<tr>
<td>RR 65%</td>
<td>0.5</td>
<td>1.45</td>
</tr>
</tbody>
</table>
3.5.7. Prediction of Carbon in Ash (CIA)

To provide guidance to the utility power companies to take cost effective measures by reducing the unburned carbon in fly ash (CIA), it is important to measure the unburned carbon in ash (CIA). Also, predicting unburned carbon in fly ash is a significant measure for determining the efficiency of coal combustion in a power plant. One of the objectives of this study was to determine unburned carbon in ash (CIA) for different firing conditions. Table 3.6 compares the numerically calculated CIA percentage with experimental data [205]. CIA at the particles exiting the furnace depends on several factors, such as the particle size distribution, oxygen concentration and residence time. Comparison of carbon-in-ash (CIA, %) measurement for selected cases were presented in Table 3.6. Numerical results exhibit a similar trend with the experimental ones, e.g. improved burnout under oxy-fuel firing conditions compared to air combustion. This can be attributed to longer residence times for the particles as well as to the higher oxygen concentration in the furnace.

3.6. Summary

The main objective of this work was to develop a complete three dimensional CFD model to examine the radiative and convective heat transfer performance and burnout effect considering the combustion of Russian coal in air-firing and three different RFG based combustion cases. In different combustion cases, radiative heat transfer was predicted and compared with the available experimental data. The numerically calculated results showed a reasonable agreement against the measured radiative heat flux on the furnace radiative wall. Different combustion cases were further illustrated presenting and discussing on the basis of temperature
distribution, species concentration distribution, and velocity distribution in
the furnace. Flame stability had been confirmed using the aerodynamic
effects of primary and secondary inlets of the burner in the IFRF burner. The
numerical results showed that the flame for the RFG fired case was relatively
concentrated in the central position compared to air-fired flame. There was
understandable combustion delay in RFG fired combustion compared to air-
fired case. Results showed that the flame temperature distribution and O2
concentration of RR75 combustion case were similar to the air-fired case.
Also, highest peak radiative heat flux and highest flame temperature with
confined structure corresponded to the lowest recycle ratio of RR 65%. The
flame temperature of RR65 % was higher, and the flame structure was
shorter and more confined. For retrofitting purpose, a working range for the
selected fuel under different cases was developed. From the presented
working range, air equivalent radiative heat flux observed at a RR of 71%
where convective heat flux increases as the radiative heat flux goes
downstream with the increase of RR. Air equivalent flame temperature was
found to be at RR of 72 %. While predicting the carbon in ash, reasonable
agreement was observed when compared with the experimental data.
Burnout improved under oxy-fuel firing conditions compared to air
combustion.
Overview: In this chapter, a 3D computational fluid dynamics (CFD) modelling of the co-combustion of pulverised Russian coal with highly volatile biomass called Shea meal having different blending ratio (20% and 40%) has been considered in a 0.5MWth combustion test facility (CTF) for air and CO₂-rich environment. A commercial CFD tool called AVL Fire version 2009.2 coupled with the user defined subroutines for the aerodynamics of irregular shaped biomass particle, devolatilization and char Combustion modelling is used. Results are validated comparing against the experimental data to examine the effects of co-firing under different operating conditions and a reasonably good agreement was observed with the differences in range of 5-10% with the experimental data. Operating conditions were varied with the recycled ratios (RR) (68%, 72% and 75%) and the biomass sharing (20% and 40%). Results are presented in terms of temperature distributions, CO₂ concentrations, and the effects of co-firing ratio under different oxy-fuel combustion. With the increase of biomass sharing from 20% to 40%, the volume of the flame increases, but the flame stability and the peak temperature decreases due to higher volatile content in the biomass. The relationship of the peak and mean flame temperature and furnace exit temperature with the normalized total flow (NTF) and normalized O₂ flow (NOF) are presented. The heat transfer is significantly manipulated by the biomass sharing with different recycled ratio. The working range for the co-firing of 20% biomass sharing suggested that optimum recycled ratio (RR) for flame temperature and radiative heat transfer to be closely matched with air-firing found at 71%, but for 40% sharing, a value of RR70% may be needed. Finally, unburned carbon in ash (CIA) is predicted and improved
burnout is observed in oxy-fuel cases with higher biomass sharing. This CFD modelling study highlights the possible effects of varying the fuel on ignition environment and heat transfer characteristics of a small scale furnace, emphasizing the minor reforms that may be needed when transforming to higher biomass sharing co-firing.

4.1. Introduction

Natural resources like, oil and gas are likely to be limited within this century according to literature [281, 282]. Fossil fuels are responsible for major electrical energy source in the world [101] but fossil fuels are depleting. Also, due to increased environmental impact of emission on climate change from power generation plant based on fossil fuel combustion, efforts have been given to the development of more sustainable means of generating power. One possible ways of the reduction of emission maintaining power generation could be changing the fuel supply especially from conventional to renewable and sustainable energy sources. So, one of the principal means of mitigating the future energy crisis is expanding the use of renewable energy and is an approach to attain sustainable development in the world. Biomass fuels are carbon dioxide (CO₂)-neutral energy sources [26]. They always represent the less expensive power generation option when compared to other renewable sources [37, 38]. Co-combustion of biomass offers higher efficiency when fired with coal in power plants [36] compared to dedicated biomass power plants. Co-combustion of biomass fuel may be the significant substitution of fossil fuel in the existing technologies.

Several experimental investigations in laboratory/pilot and industrial scale facilities were conducted to demonstrate the importance of co-firing of different biomass fuel with coal. But, the knowledge of biomass co-
combustion and its subsequent detailed thermal, chemical, and fluid-mechanical mechanisms is still far from sufficient. In last decade, many efforts have been devoted to co-combustion of different coal with biomass to determine the fundamentals of ignition, emissions and the performance of the furnace and to identify the special effects of co-combustion of biomass on the flame characteristics, species emission, and unburned carbon in ash [91, 177, 191-194]. A detailed analysis of co-combustion phenomenon is given from technical and environmental point of view for the reduction of CO₂ emissions in Ref [189]. Performance of co-firing of biomass depends on physical and chemical characteristics and the availability of the selected biomass. It is found from the literature that several types of biomass particle are considered in various experiments conducted [31, 72, 84, 88, 180, 184, 187, 188]. These studies were conducted to evaluate the influence of co-firing on boiler plant performance, combustion chemistry etc. Little study has been reported for the oxy-fuel co-firing cases in literature. Smart [205] conducted an experimental study for the oxy-fuel co-firing of biomass with coal. The objective of the study was to investigate the radiative, convective heat transfer and burnout performance for the co-combustion of Russian and South African coal with various percentage of sharing of biomass includes Shea meal and saw dust in a 0.5MWth combustion test facility.

In industrial power plants, combustion always involves emissions. In order to reduce the pollutant emission (mainly CO₂ emissions), a number of CO₂ capture technologies, can be implemented for continuing use of fuel sources [22, 60, 102]. In recent years, many efforts have been devoted to the development of oxy-fuel technology [23, 105, 113, 114]. Besides oxy-fuel concept, several newly developed techniques are suggested in literature [16, 106, 283]. Several small scale experimental studies [117-119, 121] have been conducted at various combustor design and numerical attempts have been
made to computationally model the combustion in oxy fuel environments in recent years [15, 62, 95, 96, 99, 100, 127, 129, 130, 230, 284, 285]. From the literature [126, 208, 210], it was found that oxy-fuel technology can be retrofitted to existing power station combining co-firing of biomass for the reduction of pollutant emissions.

CFD modelling method for oxy-fuel co-combustion of biomass is a significant challenge. Only a few CFD attempts in biomass co-combustion in boilers and furnaces are found in literature in small or large scale [71, 78, 82, 92, 93, 216, 286, 287]. But the detailed mechanism in chemical and thermal reactions and subsequent mechanisms on the influence of irregular shaped particle are not explored in details. Few researchers attempted to simulate the three dimensional large scale tangentially fired power generation plants using CFD [73, 83, 92, 128]. But there is little study on the modelling of co-firing of coal and biomass under oxy-fuel combustion environment. The objective of this numerical study is to determine the effect of co-firing in oxy fuel combustion of coal (Russian coal) and biomass (Shea meal) at different co-firing ratios in order to explore the technical challenge such as the radiative and convective heat transfer performance of the boiler.

This CFD study will attempt to model the co-firing considering the issue related to design or retrofit an existing furnace. The optimum co-firing ratio of coal and biomass and their effects on the boiler performance will be addressed. Finally, a unique balance of radiative and convective heat transfer with recycled ratio (RR) will be determined.
Figure 4.1: Schematic diagram of computational grid, burner design with coordinate system (all dimensions are in mm scale).

4.2. Experimental Study Considered

The data of combustion test facility (CTF) considered in this study is a 0.5 MWth lab scale furnace for coal and biomass combustion under air/oxy-firing condition conducted by Smart [205]. Ref. [205] is the experimental investigation of the effect of radiative and convective heat transfer and burnout effects of the co-combustion of Russian and South African coal with saw dust and Shea meal at different combustion environment conducted. The detailed specification and dimensions of the furnace are given in [205-207]. Figure 4.1 shows a schematic diagram of the CTF with computational grid used. The CTF consists of a burner and 800 mm refractory lined square furnace and approximately 4000 mm long. The exit of the furnace is 2180 mm convergent section. The CTF is equipped with an aerodynamically air staged burner (AASB) [129] as shown in Figure 4.1. The dimension of the modelled burner is given in [60, 205-207]. From the burner design, it was seen that the fuel with carrier gas were supplied through primary annulus and the swirl combustion air was delivered through secondary annulus. The swirl is
applied in accordance with the experimental setup given in Ref [205]. In the experiment, radiative heat flux was measured by a MEDTHERM [261] digital heat flux meter on the furnace wall through measuring ports.

Table 4.1: Fuel Properties used in this study

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>Coal</th>
<th>Biomass</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Proximate analysis, ( % ar)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volatile matter</td>
<td>33.55</td>
<td>56.47</td>
</tr>
<tr>
<td>Ash content</td>
<td>11.98</td>
<td>4.72</td>
</tr>
<tr>
<td>Fixed carbon</td>
<td>48.27</td>
<td>27.26</td>
</tr>
<tr>
<td>Total moisture</td>
<td>6.23</td>
<td>11.58</td>
</tr>
<tr>
<td><strong>Ultimate analysis, ( % ar)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C content</td>
<td>65.91</td>
<td>44.58</td>
</tr>
<tr>
<td>H content</td>
<td>4.59</td>
<td>5.88</td>
</tr>
<tr>
<td>N content</td>
<td>2.09</td>
<td>2.60</td>
</tr>
<tr>
<td>S content</td>
<td>0.34</td>
<td>0.24</td>
</tr>
<tr>
<td>O content</td>
<td>8.89</td>
<td>38.43</td>
</tr>
<tr>
<td>GCV, MJ/kg</td>
<td>27.098</td>
<td>17.362</td>
</tr>
</tbody>
</table>

Table 4.2: Particle distribution of fuels used

<table>
<thead>
<tr>
<th>Size (µm)</th>
<th>Fuel type(% of passing)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coal</td>
</tr>
<tr>
<td>300</td>
<td>99.7</td>
</tr>
<tr>
<td>212</td>
<td>99.2</td>
</tr>
<tr>
<td>150</td>
<td>97.6</td>
</tr>
<tr>
<td>106</td>
<td>91.6</td>
</tr>
<tr>
<td>75</td>
<td>77.4</td>
</tr>
<tr>
<td>&gt;300</td>
<td>0.30</td>
</tr>
</tbody>
</table>
4.3. **Source of Data for CFD Input**

In this numerical study, co-combustion cases were modelled considering pulverised Russian coal and Shea Meal (biomass) as fuel in a 0.5MWth combustion test facility (CTF). The coal and biomass are characterized with gross calorific value (GCV) of 27,098 kJ/kg and 17,362 kJ/kg respectively. The fuel properties are summarized in Table 4.1. In order to validate the model, the experimental data in Ref. [205] for co-firing of coal and biomass are compared with the CFD data of radiative heat flux on the furnace wall. Fuel particles are introduced in CTF through primary annulus fitted with Rosin-Rammler distribution. The fuel particles sizes ranged between 75µm and 300µm. For the irregular shaped biomass, around 30% of passing of particle has a maximum size of more than 200µm. The length to diameter ratio for biomass particle is assumed to be 10.0 [128]. The particle distribution for coal and biomass were presented in Table 4.2. For initial heating of the CTF, gas was introduced through primary annulus up to the stabilization of flame temperature. The flow rate, temperatures and oxygen concentrations for different registers are varied with the recycled ratios. But, a constant carrier gas flow was maintained with 15 m/s for all the cases considered. The operating conditions in accordance with the experiment for co-firing cases are shown in Table 4.3. The temperatures were maintained at 70° C and 270 °C at the inlets of primary and secondary respectively. The swirl effect is significant in the combustion phenomenon. Constant secondary swirling flow is maintained with the swirled number of 0.6 for all the experiments. The wall properties were defined with thermal resistance given in ref [76] assuming the value of emissivity, $e = 0.85$ [278] for the furnace wall.
Table 4.3: The inlet flow field parameters of all the combustion cases for primary and secondary inlet of the burner.

<table>
<thead>
<tr>
<th>Inlet</th>
<th>Flow field parameters</th>
<th>Combustion Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Air</td>
</tr>
<tr>
<td>Primary inlet</td>
<td>Mass flow rate (kg/h)</td>
<td>110.0</td>
</tr>
<tr>
<td></td>
<td>Axial velocity (m/s)</td>
<td>15.0</td>
</tr>
<tr>
<td></td>
<td>Inlet temperature, K</td>
<td>343</td>
</tr>
<tr>
<td>Fuel supply</td>
<td>80% coal, kg/h</td>
<td>54.4</td>
</tr>
<tr>
<td></td>
<td>20% biomass, kg/h</td>
<td>21.2</td>
</tr>
<tr>
<td></td>
<td>60% coal, kg/h</td>
<td>40.8</td>
</tr>
<tr>
<td></td>
<td>40% biomass, kg/h</td>
<td>42.4</td>
</tr>
<tr>
<td>Secondary inlet</td>
<td>Flow rate (kg/h)</td>
<td>620.0</td>
</tr>
<tr>
<td></td>
<td>Axial velocity (m/s)</td>
<td>39.76</td>
</tr>
<tr>
<td></td>
<td>Angular velocity (rad/s)</td>
<td>371</td>
</tr>
<tr>
<td></td>
<td>O₂ concentration, %</td>
<td>23.15</td>
</tr>
<tr>
<td></td>
<td>CO₂ concentration, %</td>
<td>00.0</td>
</tr>
<tr>
<td></td>
<td>Inlet temperature, K</td>
<td>543</td>
</tr>
</tbody>
</table>

4.4. Investigated Cases

This numerical study is to explore the effect of radiative and convective heat transfer performance and burnout of the co-firing of coal and biomass in air-firing and oxy-firing cases. For oxy-fuel combustion, different recycled ratios (RR) were considered in this study, i.e., RR68% (total O₂ 26.6% and total CO₂ 73.4% by mass), RR72% (total O₂ 23.4 % and total CO₂ 76.6% by mass) and RR75 % (total O₂ 21.0% and total CO₂ 79% by mass). The biomass was co-fired with the coal at a mass ratio of 20% and 40% for air firing and the selected cases of oxy-firing. In all the cases, the total mass flow of fuel was maintained to keep the input load of the plant at 0.5MWth. The fuel mass
flow rates into the plant for different co-firing ratios are shown in Table 4.3. One of the main concentrations of this study is to investigate the variation of flame temperature, brightness and luminosity in different combustion environment and to relate the output data in air to oxy-fuel cases for the purpose of retrofitting. Development of a unique balance between convective and radiative heat transfer characteristics is also important.

4.5. Computational Method

A commercial computational fluid dynamics code AVL Fire version 2009.2 was considered for the modelling of co-firing under different operating conditions to predict the temperature, flow characteristics, species generation, radiative heat transfer etc. In this study, gas-solid two phase flow is simulated using the Eulerian-Lagrangian approach (See section 3.3.1). In order to solve the chemical reactions such as devolatilization and char burnout for two different types of fuel having different proximate and ultimate data and related factors, user-defined subroutines were developed and introduced to the CFD code.

*Chemical Reactions:* In the present study, three-step reactions have been considered for the co-combustion process of hydrocarbon (HC) fuel due to some limitations observed in single-step reaction scheme [96, 230]. In the presence of CO₂ and H₂O, three steps scheme is appropriate for air-firing case as well as oxy-firing case. As Global power law (one-step reaction) cannot precisely capture the effect of the temperature and oxygen partial pressure dependency on the char combustion kinetics and CO/CO₂ production rate. Hurt and Calo [98] developed a multi steps semi global kinetics for char combustion model and recently Nikolopoulos et al. [16] implemented in numerical code. Al-Abbas [95] investigated the effects of
different char combustion model using single step and multi steps (two steps and three steps) reaction mechanisms in small scale furnace. Based on previous studies of the authors [62, 95, 96, 99, 100, 230], the two step reaction mechanism was used in this work since it was found to be appropriate for modelling the char combustion process in a small scale furnace.

Homogeneous reaction for the devolatilization process:

\[
\text{CH}_4 + \text{O}_2 \rightarrow \text{CO} + \text{H}_2 + \text{H}_2\text{O} + \text{Heat} \quad \text{Equation (4.1)}
\]

\[
\text{CO} + \text{H}_2\text{O} \rightleftharpoons \text{CO}_2 + \text{H}_2 \quad \text{Equation (4.2)}
\]

\[
\text{O}_2 + 2\text{H}_2 \rightleftharpoons 2\text{H}_2\text{O} \quad \text{Equation (4.3)}
\]

Heterogeneous reactions for the char oxidation process:

\[
\text{C}_{\text{char}} + \frac{1}{2} \text{O}_2 \rightarrow \text{CO} \quad \text{Equation (4.4)}
\]

\[
\text{CO} + \frac{1}{2} \text{O}_2 \rightleftharpoons \text{CO}_2 + \text{Heat} \quad \text{Equation (4.5)}
\]

*Turbulence:* For Turbulence modelling, the k-ε model is considered in this study. This model is widely used and applicable for the flow in industrial cases. Comparatively, reasonable and realistic output data are predicted by this model. This standard k-ε model is developed in CFD codes as described in Ref [270, 288]. The values of the turbulent coefficients are given in Ref [96].

*Heat Transfer:* Due to high concentration of CO₂ in the combustion chamber [271], determination of the Radiative heat transfer is important in modelling the combustion. Several models are available in literature for radiative heat transfer formulation. Most of the suggested models are categorized under the weighted-sum-of-gray-gases models (WSGGM) [203]. The WSGGM is very important for gas radiation calculation in oxy-firing cases, where CO₂ and H₂O present in high concentration [129, 289]. As suggested, the discrete
transfer radiation method (DTRM) [272] is considered in this numerical study. In DTRM method, the radiation intensities are defined assuming single ray with constant temperature where the emissivity largely dependent on the temperature and composition of the gases [273]. The convective and radiative heat transfer can be calculated during the flow interaction between the gas and particle in the furnace (See Section 3.3.5).

*Particle combustion:* Particle combustion modelling is composed of several processes including gas phase and particle phase modelling. The gas phase is described by Navier Stokes conservation equations under the Eulerian approximation/formulation. The heat transfer, particle trajectories, turbulence are coupled through the source term in the general form of Eulerian transport equation used given in Ref. [263] (See Section 3.3.2).

In the particulate phase model, discrete droplet method (DDM) [264] is considered. This method includes the momentum exchange, heat and mass transfer phenomena. The differential equation for a solid particle is defined as follows from Ref. [60] where the coefficient are given in [96, 219]:

\[
m_p \frac{du_{\text{idr}}}{dt} = \vec{F}_{\text{idr}} + \vec{F}_{\text{ig}} + \vec{F}_{\text{react}} \quad \text{Equation (4.6)}
\]

\[
\vec{F}_{\text{idr}} = D_f \cdot u_{\text{rel}} \quad \text{Equation (4.7)}
\]

\[
\vec{F}_{\text{ig}} = V_p \cdot (\rho_p - \rho_g) \cdot g_i \quad \text{Equation (4.8)}
\]

\[
\vec{F}_{\text{react}} = V_p \cdot \left( \frac{\rho_{\text{ef}}}{\rho_p} \right) \quad \text{Equation (4.9)}
\]

\(D_f\) is the drag function depending on the drag coefficient of the droplet. It is an important factor in particle aerodynamics. Accurate value of the drag coefficient depends on the cross sectional area and the Reynolds number of the particle.
For spherical shaped particle, drag is simple. But for irregular shaped particle flow, the aerodynamics of the fuel particle is largely dependent on the deviation of shape. In this study, coal particle is assumed to be spherical in shape, but biomass particle is assumed in irregular shape. From the various formulations in literature for the drag coefficient of a single sphere in this study, the drag coefficient for spherical coal particle uses the following formulation from Schiller and Naumann [219]:

$$C_D = \frac{24}{Re} \left( 1 + 0.15 Re^{0.687} \right) \quad Re < 10^3$$

$$C_D = \frac{24}{0.44} \quad Re \geq 10^3$$

Equation (4.11)

Biomass particle are considered as irregular shaped and have a large aspect ratio. A particle shape factor ($f$) is employed to permit for the possessions of non-spherical shape. This is important because the shape significantly influences the aerodynamic behaviour of the biomass particle. The shape factor ($f$) is the ratio of the surface area of an equivalent sphere of irregular shaped particle to the actual particle surface area. In this study, in order to consider the effects of deviation of shape, a user defined drag coefficient is considered in the form of a shape factor. Detail of the formulation used is documented in Ref. [218].

$$C_D = \left( \frac{24}{Re} \right) \left( 1 + b_1 Re^{b_2} \right) + \frac{b_3 Re}{b_4 + Re}$$

Equation (4.12)

$$b_1 = \exp(2.3288 - 6.4581f + 2.4486f^2)$$

Equation (4.13)

$$b_2 = (0.0964 + 0.5565f)$$

Equation (4.14)

$$b_3 = \exp(4.9050 - 13.8944f + 18.4222f^2 - 10.2599f^3)$$

Equation (4.15)

$$b_4 = \exp(1.4681 + 12.258f - 20.7322f^2 + 15.8855f^3)$$

Equation (4.16)

Where, $b_1$, $b_2$, $b_3$ and $b_4$ are functions of the shape factor, $f$. 

$$D_f = \frac{1}{2} \rho_g A_p C_D |u_{rel}|$$

Equation (4.10)
The Eddy Breakup (EBU) model [265, 266] is applied for all the combustion modelling which determine the latest status of \( \text{O}_2 \) and fuel required for reaction possibility. In combustion modelling, the mean reaction rate is an important parameter which is defined as a function of the local flow properties [266] given in Ref. [60].

In the particulate phase model, two very important terms in the modelling of combustion are devolatilization and char oxidation. In devolatilization, reaction model proposed by Badzioch and Hawksley [268] is considered where the rate of volatile production depends on the temperature history of the particle and the rate constant. The value of the Arrhenius rate constants such as pre-exponential factor \((A_v)\) and activation energy \((E_v)\) is dependent on the proximate and ultimate approximation of the fuel data [70]. Selection of these reaction kinematics is an important issue for modelling proper devolatilization. Also, the generation of char from the process of devolatilization largely depends on these factors which results in determining the amount of unburned carbon in ash. Average values for the coal to activation energy \((E_v)\) of 230 kJmol\(^{-1}\) and a pre-exponential factor \((A_v)\) of \(4.2 \times 10^{14}\) s\(^{-1}\) were used in this study [60, 82, 290]. For shea meal as a co-fired fuel, there is no such available experimental data on the behaviour of heating up of the fuel in the furnace. The values of \(A_v=6 \times 10^{13}\) s\(^{-1}\) and \(E_v= 2.5 \times 10^8\) Jkgmol\(^{-1}\) were considered, based on previously used data in Refs. [32, 82, 290] for biomass combustion having similar physical and chemical characteristics. (For detailed modelling, See Section 3.3.3).

When the devolatilization is completed, the remaining amount of particle is char and ash. This char will react with the surrounding gases steadily [269]. In this study, the char combustion is modelled with global power-law [27] where diffusion of \( \text{O}_2 \) is responsible for the oxidation rate of char particle.
The kinetics parameters used for char modelling are as follows: for coal particles, activation energy ($E_c$) of $155 \text{ kJ mol}^{-1}$ [60] and pre-exponential factor ($A_c$) of $497 \text{ kg m}^2\text{s}^{-1}(\text{N m}^2)^{-1}$ [60] were used, while for biomass, $E_c = 74.8 \text{ kJ mol}^{-1}$ [291] and $A_c = 0.04 \text{ s}^{-1}$ [32] were considered. More detailed information about the modelling formulations is discussed in some of the recent papers on for small scale and large scale combustion cases [60, 62, 95, 96, 100, 230, 292].

![Figure 4.2: Average flame temperature predicted for 20% biomass under air-firing case.](image)

### 4.6. Numerical Method

In the CFD code used, user defined sub-routines are incorporated for the modelling of combustion using the finite volume method (FVM). The SIMPLE algorithm, the discrete form of the continuity equation is used to update the pressure and velocity fields so that the velocity components obtained from the solution of momentum equations satisfy the continuity equation. In order to be consistent with the experimental work, initial start-up of the furnace is accomplished by the gas burning. After achieving quasi-steady state, fuel particles are introduced in the CTF. The total number of particles per second is set to 10000, which is 25 particles per time step of
0.0025 s used for all the cases considered in this study. Results were averaged after the stabilization of the flame over 35,000 time steps. Figure 4.2 shows the average flame temperature predicted for 20% biomass under air-firing case. Regarding convergence, a standard of $10^{-4}$ for absolute residuals is considered. In order to reduce computational time as well as to build up confidence level, a grid independency test was considered for the co-firing of coal with 20% biomass under air firing case. Three different grids were considered having 500,000, 650,000 and 800,000 cells with similar meshing scheme. Finer mesh was adopted in the burner region to the rest of the computational domain. Mass fraction distribution of species such as $O_2$ and $CO_2$ in radial direction at 0.3m from burner exit was compared (shown in Figure 4.3). It is seen from the profile that fine (800,000 cells) and medium (650,000 cells) grid systems produce similar profile compared to coarse (500,000 cells) grid system. Therefore, a 3-D non-uniform structured grid with 650,000 cells was adopted for the study.

Figure 4.3: $O_2$ and $CO_2$ mass fraction (kg/kg) distribution in radial direction at 0.3 m from burner exit for coal with 20% biomass sharing under air firing condition.
4.7. Results and Discussion

4.7.1. Radiative Heat Flux Prediction and Validation

In order to validate the CFD model developed for the co-firing, predicted radiative heat fluxes for air and oxy-fuel combustion are compared with the experimental data [205] for each cases. The variations of numerical and the experimental data of radiative heat flux in the radiative section of the CTF is studied and presented (in figures 4.4-4.7) for all the cases. In all the figures, 5% vertical variation is shown for better appreciation of the present numerical discrepancy. It is seen that in some position, numerical radiative flux deviates more than 5% compared to experimental data. A reasonable agreement has been found between the predicted and the available experimental data neglecting the discrepancy in some measurement position considering both numerical limitations as well as experimental inaccuracy. Table 4.4 shows the comparison of numerical and experimental peak radiative heat transfer measurement for all the selected cases. Therefore, the CFD predictions are deemed to provide a decent representation of the radiative heat transfer in the furnace and are considered for further investigation in modelling the co-combustion. The detail findings for the prediction of radiative heat flux for air and oxy-fuel cases are explained in the following section.

Figure 4.4 shows the radiative heat flux comparison for 20% and 40% biomass sharing in air-firing case. Predicted results shows similar trend between the numerical and experimental data [205].
Figure 4.4: Radiative heat flux distribution for air combustion case compared with the experimental data for different biomass sharing.

Figure 4.5: Radiative heat flux distribution for RR75% case compared with the experimental data for different biomass sharing.
Figure 4.6: Radiative heat flux distribution for RR72% Case compared with the experimental data for different biomass sharing.

Figure 4.7: Radiative heat flux distribution for RR68% case compared with the experimental data for different biomass sharing.
Table 4.4: Comparison of numerical and experimental peak radiative heat transfer measurement

<table>
<thead>
<tr>
<th>Cases</th>
<th>Experiment (KW/m²)</th>
<th>Prediction (KW/m²)</th>
<th>Error (%)</th>
<th>Experiment (KW/m²)</th>
<th>Prediction (KW/m²)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>385.00</td>
<td>395.36</td>
<td>2.69</td>
<td>395</td>
<td>360.56</td>
<td>8.71</td>
</tr>
<tr>
<td>RR75</td>
<td>328.00</td>
<td>318.90</td>
<td>2.77</td>
<td>---</td>
<td>294.77</td>
<td>---</td>
</tr>
<tr>
<td>RR72</td>
<td>375.00</td>
<td>380.97</td>
<td>1.59</td>
<td>328</td>
<td>340.99</td>
<td>3.96</td>
</tr>
<tr>
<td>RR68</td>
<td>435.00</td>
<td>437.85</td>
<td>0.65</td>
<td>370</td>
<td>386.67</td>
<td>4.50</td>
</tr>
</tbody>
</table>

Overall, slightly higher range of radiative flux is observed for 20% case compared to 40%. This is due less amount of moisture and lower calorific value of the biomass sharing. But experimental result show interesting profile for heat flux for 40% biomass sharing in air-firing case. Comparatively, higher value is observed compared to 20% case. This is not in line with the numerical result. For recycled ratios 68%, 72% and 75%, the comparison of the radiative heat flux between the numerical and experimental data for 20% and 40% biomass sharing is presented in Figures 4.5-4.7. It is seen for these cases that as the RR is increased, the radiative heat flux is reduced which can be explained due to O₂ enriched environment. When RR is increased by reducing the O₂ level, the radiative heat flux is decreased [205]. Comparatively higher and lower radiative heat flux is observed in the case of RR 68 and RR 75 respectively. Similar findings has been reported in the experimental work of Smart [205]. However, the experimental result for 40% biomass sharing under RR75% is not reported by Smart [205]. The volatile content for biomass is higher. It is expected that volatile matter content would proportionately increases flame length and help in easier ignition of coal leading to increase of the radiative heat flux in the combustion area. But, the higher moisture content with lower calorific
value of biomass plays the vital role. With the increase of biomass sharing to 40%, volatile fraction and moisture content increase. The dominant effect of the lower calorific value and higher moisture content of biomass depresses the effect of volatile content. Thus the principal effect of the lower calorific value and higher moisture content of biomass is to lower the flame temperature thus radiative heat flux. Better flow mixing provides higher flame temperature in the presence of high concentration of O\textsubscript{2} at lower flow rate. Thus, at lower RR, comparatively higher flame temperature as well as higher radiative heat flux is observed. Also, the characteristic of heat capacity of CO\textsubscript{2} contributes to the flame emissive properties. When RR is increased, the higher heat capacity of CO\textsubscript{2} tends to keep the flame temperature low.

When the sharing of biomass in increased from 20% to 40%, it was seen that the radiative heat flux is decreased significantly for all the cases. This can be explained on the basis of volatile presence. Higher volatile yields of biomass produce more off-gas inside the furnace. This larger volume of off-gas generates larger flame but lower temperature at higher percentage of sharing. Higher moisture content and lower calorific value depresses the flame temperature cancelling the effect of high volatile content. Due to lower flame temperature at 40% case radiative heat flux is significantly decreased.

4.7.2. Species Mass Fraction Distribution

The carbon dioxide (CO\textsubscript{2}) and oxygen (O\textsubscript{2}) mass fraction (kg/kg) distributions are presented in the burner region and the reaction zone on a horizontal plane axially along the centre of the furnace in Figure 4.8 and 4.9 respectively. Figure represents the variation of CO\textsubscript{2} for different combustion cases under different fuel ratios. Concentrations of CO\textsubscript{2} are normally varied with the RR for the oxy fuel cases as presented in the boundary conditions in
Table 4.3. Lower values of CO$_2$ concentrations are applied in the lower RR. It is seen from the figure that comparatively lower CO$_2$ is observed for air-firing cases. Significant variation is found in the concentration of CO$_2$ while comparing the air-firing case to the oxy-firing cases. The peak value of the CO$_2$ concentration is seen in the reaction zone of the furnace. This statement is in line of the generation of peak flame temperature in the reaction zone. Due to presence of higher percentage of volatile matter in biomass, O$_2$ is consumed quickly in homogeneous chemical process. After the combustion of volatile matter, char is reacted with the surrounding O$_2$ and CO$_2$ is formed in the combustion area. More details about this phenomenon are described in Ref. [293].

In air firing case, maximum CO$_2$ concentration observed 0.185 by mass (kg/kg) for 20% and 40% biomass sharing respectively. In Oxy cases, the concentration of CO$_2$ is much higher. But with the decrease of RR, this fraction goes down. The maximum concentrations of CO$_2$ mass fractions in the furnace were equal to 0.915, 0.91, and 0.895 wt% for the RR75, RR72 and RR68 respectively for 20% biomass. While maximum concentrations of CO$_2$ mass fractions equal to 0.90, 0.91 and 0.89 wt% for the respective cases for 40% biomass sharing. Others species such as CO$_2$, CO,HC, H$_2$O and H$_2$ mass fraction distributions along the furnace centre line are presented in Figures 4.10-4.14.
Figure 4.8: Predicted CO\(_2\) mass fraction distribution for different biomass sharing, (a) 20% biomass sharing and (b) 40% biomass sharing.
Figure 4.9: Oxygen (O₂) mass fraction distribution on the horizontal plane for different cases considered (40% Biomass sharing).
Figure 4.10: CO$_2$ mass fraction distribution on axial direction for 20% Biomass sharing for different combustion environment.

Figure 4.11: CO mass fraction distribution on axial direction for 20% Biomass sharing for different combustion environment.
Figure 4.12: HC mass fraction distribution on axial direction for 20% Biomass sharing for different combustion environment.

Figure 4.13: H₂O mass fraction distribution on axial direction for 20% Biomass sharing for different combustion environment.
**Figure 4.14:** Species (H\textsubscript{2}) mass fraction distribution on axial direction for 20% Biomass sharing for different combustion environment.

**Figure 4.15:** Predicted flame temperature distribution (K) for different biomass sharing, (a). 20% biomass sharing, (b). 40% biomass sharing at a distance of 0.3 m from the burner.
Figure 4.16: Flame temperature distribution on the horizontal plane for different Biomass sharing under air firing case.

Figure 4.17: Flame temperature distribution on the horizontal plane for different Biomass sharing under oxy-firing (RR 75%) case.
Figure 4.18: Flame temperature distribution on the horizontal plane for different Biomass sharing under oxy-firing (RR 72%) case.

Figure 4.19: Flame temperature distribution on the horizontal plane for different Biomass sharing under oxy-firing (RR 68%) case.
### 4.7.3. Flame Temperature Distribution

The flame temperature distributions for all the cases are presented in Figure 4.15. The visualization is shown on the vertical plane 0.3 m from the exit of the burner. It is expected that the biomass particle burned out earlier in the system and did not fully entrain downstream in the gas stream. Rather, the biomass appeared to be consumed at a relatively higher rate in the near burner region and burn in situ because of highly volatile content. For all the cases, the biomass fuel burns very close to the burner exit where the peak flame temperature are observed. With the increase of biomass sharing, possibility of ignition of fuel within the furnace increases with fuel volatility and since biomass char is more reactive than coal char; ensures that the biomass burns out early within the furnace. This may be further explained by the fact that higher volatile yields of biomass produce more off-gas during combustion. These off-gases result in the larger volume required of the CTF in order to complete the combustion. Therefore, the co-combustion flames are larger in volume. The flame is more than 1.0 m in the direction of flow for the air-firing case (as shown in the Figures 4.16-4.19). However as explained earlier, the dominant effect of the lower calorific value and higher moisture content of biomass depresses the effect of volatile content. Determining the suitable level of highly volatile biomass is important for better efficiency of the furnace. Higher flame temperature during co-firing can be achieved by injecting less biomass. When biomass sharing is increased to 40%, comparatively larger volume of flames is observed. These are illustrated in Figures 4.16 to 4.19 for air-firing and selected oxy-firing cases. Though, a larger volume of flame is observed, the peak flame temperature is reduced. The expansion of flame volume with reduced peak flame temperature is favourable for improved burnout and lower emission. Figure 4.20 shows the flame temperature distributions along the centre line of the furnace from burner exit for different co-firing cases under different oxy-
fuel conditions. The temperature distribution shows that, the addition of biomass to coal result in a decrease in gas temperature in respective oxy-fuel cases.

Combustion rate is a critical factor which depends on size of the particle during burning under co-firing condition. It can be stated that the rate of combustion decreased with the increase of biomass particle size leading to lower temperature. Large particle having size of more than 200µm are more in percentage of passing for 40% sharing (11.92%) compared to 20% sharing (5.96%). Smaller fuel size burns more completely than the larger sizes. This is also one of the reasons of decrease of flame temperature with the increase of biomass sharing.

![Figure 4.20: Flame temperature distribution along the centre line of the furnace from burner exit for different co-firing cases under different oxy-fuel conditions.](image-url)
4.7.4. **Effect of RR and Biomass Sharing on Flame Temperature**

Results from the peak flame temperature for air-firing and oxy-firing cases are presented in Figure 4.21. Figure shows that the peak flame temperature for RR68 case is higher compared to others RR cases for 20% biomass sharing. While comparing to air firing, RR68 shows higher peak temperature while RR75 and RR72 shows lower temperature. Similar observations were also made for the 40% sharing of biomass. But, with the increase of biomass sharing to 40%, decrease in the peak flame temperature is observed in the RR cases. The difference in peak flame temperature is significant with the addition of biomass. The flame temperatures can be explained by the turbulent time scale of eddy break-up model [279]. This model explains that the increased oxygen concentration appears to help the intensity of the flame, which is a result of a faster rate of devolatilization of the biomass particle near the burner and inside the furnace. When air fired is compared with oxy-firing, peak flame temperature is found at RR71% for 20% biomass case, but in case of 40% sharing, air equivalent peak flame temperature is found approximately at 70% recycled ratio. Table 4.5 shows the predicted mean and furnace exit temperature for different cases.

<table>
<thead>
<tr>
<th>Cases</th>
<th>Coal+20% Biomass</th>
<th>Coal+40% Biomass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Temp, K</td>
<td>Exit Temp, K</td>
</tr>
<tr>
<td>Air</td>
<td>1655.76</td>
<td>1338.62</td>
</tr>
<tr>
<td>RR75</td>
<td>1639.10</td>
<td>1328.94</td>
</tr>
<tr>
<td>RR72</td>
<td>1676.50</td>
<td>1332.38</td>
</tr>
<tr>
<td>RR68</td>
<td>1765.00</td>
<td>1422.70</td>
</tr>
</tbody>
</table>
Figure 4.21: Effects of oxy to air firing on peak flame temperature.

4.7.5. Effect of NTF, NOF on Biomass Sharing

The effect of normalized total flow (NTF) on peak and mean flame temperature and furnace exit temperature for 20% and 40% biomass sharing are presented in Figure 4.22. Normalized values are calculated based on Ref. [207]. With the increase of normalized total flow, peak and mean flame temperature and furnace exit temperature decreases. At higher recycled ratio or higher flow, comparatively less residence time is available. This less residence time leads to combustion happening far from the main reaction zone leading to lower temperature. Similar trend is observed for 40% cases. The average decrease in peak, mean and exit temperatures are found to be 60K, 14K and 7K respectively. Figure 4.23 shows the deviation of the numerically calculated peak, mean and exit temperature with the NOF for 20% and 40% biomass cases. It is found that with the increase of NOF, temperatures are increased. Higher $O_2$ concentration is accountable for higher temperature at lower RR.
**Figure 4.22:** Effect of normalized total flow on peak, mean flame temperature and furnace exit temperature for 20% and 40% biomass sharing.

**Figure 4.23:** Effect of normalized O\(_2\) on peak and mean flame temperature and furnace exit temperature for 20% and 40% biomass sharing.
4.7.6. **Working Range for Different Co-firing Conditions**

Figure 4.24 represents the relationship between the convective and radiative heat transfer and the flame temperature for (a). 20% sharing of biomass and (b). 40 % sharing of biomass. Relationship has been obtained comparing the normalized data of peak flame temperature and peak radiative heat flux and convective heat transfer predicted. This type of representation is useful for the purpose of retrofitting of existing condition by choosing proper RR equivalent to air firing. Defining a working range for different fuel ratio under oxy-fuel condition is important. This will provide a unique balance between convective and radiative heat transfer and flame temperature formatted inside the furnace run on air and oxy combustion. The variations of different normalized parameter for 20% sharing of biomass are presented in Figure 4.24(a). It is found from the figure that air equivalent peak flame temperature is found at RR 71%. Similar to that air equivalent peak radiative heat flux is also found at RR71%. When radiative heat flux goes down with the increase of RR, convective heat flux increases. This is due to increased convective heat transfer coefficient because of increased mass flow at higher RR. Similar to 20% sharing of biomass, working range for 40% sharing of biomass is presented in Figure 4.24(b). The trend is similar to 20% case, but air equivalent peak flame temperature and peak radiative heat flux is found at 70% RR. From this analysis, it is deduced that radiative heat flux and flame temperature is significantly manipulated by RR and retrofitting option is well justified. Also with the increase of biomass sharing, air equivalent heat flux/flame temperature is found to the lower RR.
Figure 4.24: Working range for oxy to air operation for different biomass sharing as (a). 20% biomass, (b). 40% biomass sharing.
Table 4.6: Comparison of numerical and experimental unburned carbon-in-ash (CIA) measurement.

<table>
<thead>
<tr>
<th></th>
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<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>2.1</td>
<td>2.45</td>
<td>0.70</td>
<td>2.58</td>
<td>0.5</td>
<td>2.10</td>
</tr>
<tr>
<td>RR75</td>
<td>0.5</td>
<td>1.87</td>
<td>0.50</td>
<td>1.76</td>
<td>-</td>
<td>1.50</td>
</tr>
<tr>
<td>RR72</td>
<td>0.9</td>
<td>1.47</td>
<td>0.40</td>
<td>1.49</td>
<td>0.25</td>
<td>1.35</td>
</tr>
<tr>
<td>RR68</td>
<td>-</td>
<td>-</td>
<td>0.35</td>
<td>1.23</td>
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<td>0.85</td>
</tr>
</tbody>
</table>

4.7.7. Prediction of Carbon in Ash (CIA)

In order to reduce the amount of unburned carbon and to improve the efficiency of the plant, determination of unburned carbon in ash (CIA) is significant. The comparison of CIA data is presented in Table 4.6 for different combustion cases. In order to show the comparison between the numerical and experimental data, a graphical illustration is presented in Figure 4.25. It is found that predicted data reveal a comparable trend with the experimental result. Comparatively, improved burnout under oxy-fuel firing conditions is observed compared to air combustion for different biomass sharing cases. Also, a comparison of numerically calculated CIA data for different biomass sharing is shown against the only coal combustion data from the author’s previous work [60]. It is evident that with the increase of biomass sharing, CIA amount is decreased in most of the cases. Amount of CIA depends on several factors such as particle size, combustion environment and residence time. The decrease of overall carbon in ash content for increased biomass sharing is not only due to improved combustion conditions which favour coal particles but also the contribution of both fuels to the favourable result.
4.8. Summary

The objective of the work was to develop and validate a three dimensional CFD modelling for co-firing of coal with biomass sharing (20% and 40%) under different oxy-fired operating conditions. The model developed for coal combustion modelling in previous study was modified for using multiple fuels (coal and biomass) having different properties and sizes. In order to attain confidence, a validation against experimentally measured radiative heat flux was performed. It was found that the increase of biomass sharing was responsible for increasing the volume of the flame shape, but the peak temperature decreased. Finally air equivalent peak flame temperature and peak radiative heat flux were observed at the RR of 71% and 70% for 20% and 40% biomass sharing respectively. Comparatively improved burnout was observed in oxy-fuel cases with higher biomass sharing.
CHAPTER 5. Application of Straw Co-firing in a 30 kW Swirl Stabilized Furnace for Below Zero Emission

Overview: The present study investigates the combustion behaviour of straw in air and O₂/CO₂ mixtures. Reference air-fuel and oxy-fuel (25%, 30% and 35% O₂) cases were considered maintaining a constant thermal load of 30 kW in a semi-technical scale once-through swirl-stabilized furnace. The main objective of this study was to illustrate the impact on the combustion characteristics including flame temperature, burnout, and emissions for pure coal to pure straw combusted in air and oxy-fuel atmospheres. This work has shown significant changes to the fundamental combustion characteristics for straw when burned in the O₂/CO₂ atmosphere compared to air firing case. Comparatively higher flame temperatures were observed for oxy-firing case. It was found that with 20% straw sharing, sensible performances were observed similar to that of 100% coal combustion. The CO levels are predicted to decrease in the downstream section during oxy-fuel combustion compared to air-firing flames due to O₂ availability. Also a critical analytical analysis was conducted to investigate the heating performance for straw particle of different sizes (100 µm, 330 µm and 1000 µm). The heating profiles show significant differences between the three particle sizes assuming isothermal temperature gradient and heating by both radiation and convection. The possibility of burnout of the larger straw particle size is less due to less residence time in air-firing compared to oxy-firing case. The burnout is reliably advanced during oxy-fuel combustion to 99.8% than air firing.
5.1. Introduction

The demand of electrical power in the developing countries are increasing day by day [294]. Available energy sources are fossil fuel, wind, solar, hydro, ocean and geothermal etc. [295-297]. In order to keep up with the demand of electricity, a number of coal based power plants are recently being constructed. This is due to the fact that compared to others fossil fuel resources, coal is a cheaper and more abundant resource [23, 298]. According to reference given in [69], out of the 62 countries that produce electricity using biomass, USA leads with a 26% of world production. It is followed by Germany at 15%, whereas Brazil and Japan both produce 7% of electricity of world production. Compared to these countries, usage of biomass in Australia is in the early stage. On the other hand, global warming is an issue gained significant attention in recent years which is very much connected to the carbon dioxide (CO$_2$) emissions. The main reason of the shifting from a fossil fuel to renewable energy based production is to reduce the emission of greenhouse gases, mainly CO$_2$.

As the power plants are assumed as the main source of the generation of CO$_2$ emission, so the main focus is connected to their technologies and operations. There are several technologies called carbon capture and storage (CCS) system for power plants which includes pre-combustion, post-combustion and oxy-fuel (OF) combustion technology [22, 127, 299]. The main theme of these CCS systems is the reduction of CO$_2$ emissions. The characteristics and fundamentals of each CCS systems are described in recent literatures [298, 300-305]. Among all the CCS systems available, implementation of oxy-fuel combustion [298, 306-309] is significant. In order to clarify the influence of the overview of such technology, more research is must. In last two decades, many small scale and lab/industrial scale demonstrations have been conducted and positive indication has been pointed out to burn coal in oxy-fuel environment. Besides
these technologies, a number of recent technologies such as membrane separation, chemical looping combustion (CLC), carbonation-calcination cycles, enzyme-based systems, ionic liquids, mineralization [310], etc. execute the likelihood to considerably decrease the emissions concerned with carbon capture from power plants [303, 311-313]. However, these technologies have not been demonstrated at sufficient scales for industrialization.

In recent years, utilization of renewable fuels in industrial power plants with CCS system has attracted the researcher’s attention. Co-firing coal with biomass is a relatively easier way of reducing CO$_2$ emissions from fossil fuel fired power plants [195]. At the same time, there are some disadvantages of using biomass in a traditional power plant [3, 55]. However, it is suggested that the biomass share of the fuel blend is typically kept low in order to ensure that residual products can be utilized. The combination of CO$_2$ neutral fuels with CCS opens up a possibility of extracting CO$_2$ from the atmosphere. Oxy-fuel combustion can be applied to biomass as well as to coal and the use of CO$_2$ neutral fuels induces the potential of achieving an overall negative CO$_2$ emission from the power plant. In relation to that, few experimental investigations have been conducted using straw as a co-fired fuel under air and oxy-fuel environments. It is anticipated that advance effort on co-firing of biomass (like straw) and coal in oxy-fuel environment will result in comparable changes to the burning characteristics. Also, this will provide the opportunity for retrofitting the plant by using biomass type fuel in a dedicated coal fired furnace. However, this area of research is still relatively young when considering suspension-fired boilers and research on oxy-fuel combustion of pulverized biomass could thus also be beneficial to the research within the conventional air-firing area. Recently, a number of experimental and computational fluid dynamic (CFD) models were developed to investigate the effect of coal combustion in small and large scale furnace [14, 62, 96, 100, 125, 292, 314]. Compared to only coal combustion, few
co-firing of biomass modelling and small scale experimental works were
tried by several researchers [59, 73, 74, 86, 89, 158, 194, 315-317]. Few
authors considered the low-NOx heavy-oil swirl burner developed for the low-
NOx heavy oil combustion in a lab-scale furnace [318]. Recently, some authors
justified the usage of bio-fuel as an efficient energy sources in different sectors
[319-323].

Straw is the one of the most available biomass fuel in the environment. Few
experimental investigations have been conducted using straw as a co-fired fuel
under air and oxy-fuel environments. Pedersen [184] conducted a detailed
experiment on co-firing straw and pulverized coal in a 2.5 MWt pilot-scale
burner where fractions of straw in the range of 0-20% on a thermal basis were
used in the full-scale experiment, and 0-100% on a thermal basis in the pilot-
scale experiment. They found that an increase in fraction of straw in the blend
reduces NO and SO$_2$ emissions. Toftegaard [220] conducted an experimental
study by introducing biomass in carbon capture power plants for the
combustion of coal and biomass combustion under air and oxy-fuel
atmospheres in a swirl stabilized furnace. In another analysis of Kate Wieck-
Hansen [187], co-firing coal and straw in a 150MWe power station, has been
demonstrated. Andersen [188] conducted experiments on the deposit formation
in a 150 MWe Utility PF-boiler during co-combustion of coal and straw at the
Danish energy company.

The objective of this CFD study is to improve the fundamental knowledge on
combustion of different types of fuels in a swirl stabilized furnace by clarifying
the effect of the change in combustion atmosphere on fuel burnout: flame
temperatures, emissions of polluting species when pure biomass (straw) and
blends of coal and biomass are combusted in air and oxy-fuel atmospheres. The
present work will lead to the identification of reference operating conditions
which enables a direct comparison of combustion in air and oxy-fuel atmospheres. AVL Fire version 2009.02 will be used for the modelling purpose.

![Schematic diagram of the computational domain of the 30kW Swirl stabilized furnace (all dimensions in mm)](image)

**Figure 5.1:** Schematic diagram of the computational domain of the 30kW Swirl stabilized furnace (all dimensions in mm)

### 5.2. Physical Model Setup & Fuel Characterization

This numerical study on the combustion characteristics of biomass (straw) with coal is conducted in a semi-technical scale once-through 30 kWth swirl-stabilized furnace. The details of the furnace has been considered from the experimental work given in Ref. [324]. The schematic diagram of the 30 kW
down-fired solid fuel combustor, shown in Figure 5.1 has an inner diameter of 315 mm and a height of approximately 1.9 m. The experimental setup of the combustion chamber is insulated with 80 mm two-layer refractory lining and cooled with room-temperature cooling through a void between the reactor shell and an outer insulation shell. There are total 8 measuring ports along the furnace chamber as presented in figure. The ports are numbered 1 to 8, starting with 1 from the top.

The positioning of the ports is shown in Figure 5.1. As the reactor is a once-through type, there is no duct for recirculating flue gas in oxy-fuel operation.

As shown in Figure 5.1, the swirled stabilized burner is mounted on top of the combustion chamber. A detailed diagram and dimension of the burner is given in Figure 5.2. It is seen that the burner is mainly consist of three tubes, two for primary and secondary oxidant and a separate natural gas inlet which is used during reactor heat-up and during the transition to the solid fuel flame. Fuel particles are supplied into the central, primary burner tube. The primary oxidant flow is given directly into the central burner tube. The split between the two primary oxidant flows is considered in order to achieve the best stability of the solid fuel feeding. The secondary oxidant is introduced in the burner in two separate streams, an axial flow and a tangential flow. The latter is responsible for creating a swirling motion. It is mentioned in the experimental procedure that the swirl number is adjusted by choosing the ratio between the axial and tangential flow. However, in the present CFD studies, a constant swirling flow is considered for the selected co-firing cases under air-firing and oxy-firing conditions.
Figure 5.2: A Detailed diagram and dimensions of the burner used (all dimensions in mm)

Table 5.1: Properties of coal and straw particles used

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Proximate analysis (wt%,ar)</th>
<th>Ultimate analysis (wt%,daf)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FC</td>
<td>Volatile</td>
</tr>
<tr>
<td>Coal</td>
<td>50.40</td>
<td>34.86</td>
</tr>
<tr>
<td>Straw</td>
<td>18.10</td>
<td>72.40</td>
</tr>
</tbody>
</table>

Table 5.2: Operating parameters for selection of reference air and oxy-fuel case for coal combustion

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Load</th>
<th>Fuel flow</th>
<th>Inlet $O_2$,</th>
<th>$\lambda$</th>
<th>Oxidant flow [NL/min]</th>
<th>Swirl number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>30</td>
<td>3.99</td>
<td>--</td>
<td>1.30</td>
<td>620</td>
<td>1.8</td>
</tr>
<tr>
<td>Coal</td>
<td>30</td>
<td>3.99</td>
<td>25</td>
<td>1.21</td>
<td>490</td>
<td>1.8</td>
</tr>
<tr>
<td>Coal</td>
<td>30</td>
<td>3.99</td>
<td>30</td>
<td>1.19</td>
<td>390</td>
<td>1.8</td>
</tr>
<tr>
<td>Coal</td>
<td>30</td>
<td>3.99</td>
<td>35</td>
<td>1.15</td>
<td>325</td>
<td>1.8</td>
</tr>
</tbody>
</table>

In this study, two different fuels have been utilized, a bituminous coal and pulverized straw (biomass). Proximate and ultimate analysis of the selected
fuels is summarized in Table 5.1. The coal and biomass are characterized having the heating value (LHV) of 27.09 MJ/kg and 16.40 MJ/kg respectively. The used particle size distribution for the two fuels is taken from Ref. [324]. The mean particle sizes for the coal and straw are 47 µm and 330µm respectively. The selected fuel mixtures have a 20 wt% and 50 wt% content of straw which corresponds to approximately 13 and 38 % straw on a thermal basis, respectively. The ratios of coal to straw selected for the modelling is presented in next section. For all cases considered, the solid fuel feeding system has been chosen at a set point corresponding to a thermal load of 30 kW. The constant total thermal load is settled based on the experimental study [324] considered.

5.3. Combustion Cases and Operating Conditions

This CFD study has been conducted at several combustion and co-firing conditions. A total of four different fuel compositions having different co-firing ratios have been considered. These are 100% coal, 20% straw with 80% coal, 50% straw with 50% coal and 100% straw cases. The parameters for the four fuel types include several combustion oxidant types such as air and O₂/CO₂ mixtures. For the oxy-fuel combustion, oxidant O₂ concentration values applied are 25%, 30% and 35 %. The operating parameters for the selection of reference oxy-fuel cases for coal combustion are given in Table 5.2. The applied stoichiometric oxygen excess ratios have accordingly been in the interval 1.025 to 1.3 for all the cases. A reference oxy-fuel case will be selected for further investigation. For both air and oxy-fuel cases, the primary oxidant flow is set at 20 vol% of the total oxidant flow at the reference conditions. This implies that the linear velocity of the primary oxidant leaving the burner will differ when the combustion atmosphere is changed. A similar approach (similar to experimental study) is considered for CFD simulation. However, the swirl number is kept constant to obtain similar conditions for air and oxy-fuel
modelling. The swirl number chosen for the CFD simulations in all the cases was 1.8. All other flow parameters were appropriately used for the selected swirl number for different fuel ratios. However, in the experimental study [324] considered, a range of swirl number of 1.7 to 2.0 was tested. The boundary condition for different co-firing ratios under air and reference oxy-firing cases is given in Table 5.3 and Table 5.4 respectively. There was no information given related to wall boundary condition in the experimental study considered. A constant wall temperature with no-slip boundary condition (where u, v, and w = 0) and wall emissivity were assumed for all the walls. Considering radiative properties of the wall, the value of emissivity of 0.85 is assumed for the reactor wall [278].

**Table 5.3:** Operating parameters for coal/biomass combustion in air at different fuel ratio.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Load kW</th>
<th>Fuel flow Kg/hr</th>
<th>λ</th>
<th>Oxidant flow [Nm/min]</th>
<th>Swirl number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>30</td>
<td>3.99</td>
<td>1.30</td>
<td>620</td>
<td>1.8</td>
</tr>
<tr>
<td>20% blend</td>
<td>30</td>
<td>4.33</td>
<td>1.30</td>
<td>620</td>
<td>1.8</td>
</tr>
<tr>
<td>50% blend</td>
<td>30</td>
<td>5.00</td>
<td>1.30</td>
<td>615</td>
<td>1.8</td>
</tr>
<tr>
<td>Straw</td>
<td>30</td>
<td>6.60</td>
<td>1.30</td>
<td>600</td>
<td>1.8</td>
</tr>
</tbody>
</table>

**Table 5.4:** Operating parameters for coal/biomass combustion in O2/CO2 at the reference condition.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Load kW</th>
<th>Fuel flow Kg/hr</th>
<th>λ</th>
<th>Oxidant flow [Nm/min]</th>
<th>Swirl number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>30</td>
<td>3.99</td>
<td>1.19</td>
<td>390</td>
<td>1.8</td>
</tr>
<tr>
<td>20% blend</td>
<td>30</td>
<td>4.33</td>
<td>1.19</td>
<td>390</td>
<td>1.8</td>
</tr>
<tr>
<td>50% blend</td>
<td>30</td>
<td>5.00</td>
<td>1.20</td>
<td>390</td>
<td>1.8</td>
</tr>
<tr>
<td>Straw</td>
<td>30</td>
<td>6.60</td>
<td>1.22</td>
<td>390</td>
<td>1.8</td>
</tr>
</tbody>
</table>
5.4. Modelling Procedure

The combustion modelling of coal and biomass has been conducted using a commercial computational fluid dynamics (CFD) code AVL Fire version.2009.2 coupled with user-defined subroutines. In this study, coal and straw particles combustion modelling is considered using several processes including gas phase and particle phase. The gas phase is described by Navier Stokes conservation equations under the Eulerian approximation/formulation. The heat transfer, particle trajectories, turbulence are coupled through the source term in the general form of Eulerian transport equation used given in Ref. [263] (See Section 3.3.1). In particulate phase model, a discrete droplet method (DDM) [264] is considered (See Section 3.3.2). For turbulence modelling, the k–ε model [325-329] is considered, as it is widely used and applicable for the flow in industrial cases (See Section 3.3.4). In this study, straw particles are considered as irregular shaped and have a large aspect ratio. Based on the similar type of studies given in Ref. [89], an aspect ratio (length/diameter) of 1:25 is assumed for modelling purpose. Based on the assumption, a particle shape factor (sf) is employed to permit for the possessions of non-spherical shape. The definition of shape factor is given in Ref. [59]. In order to consider these effect of larger deviation of shape of the straw particles, the chosen shape factor is incorporated in a user-defined drag correlation by using the Haider and Levenspiel formulation [218]. The reaction rate of the combustion process is controlled by the Eddy Break-up (EBU) model [96]. This model determines the reaction possibility based on oxidizer and fuel availabilities. (See Section 4.5).

Modelling of homogeneous (devolatilization) and heterogeneous (char oxidation) chemical reactions for coal/biomass combustion is important. A number of developed models are available for proper chemical reaction including devolatilization and char combustion modelling. Hurt and Calo [98]
developed a multi steps semi global kinetics for char combustion model and recently Nikolopoulos et al. [16] implemented in numerical code. Al-Abbas [95] investigated the effects of different char combustion model using single step and multi steps reaction mechanisms in small scale furnace. The authors justified that comparing to single step modelling, as multi-steps provide more accurate results. Based on this study, a three-step reaction mechanism is used in the present CFD work for the homogeneous and heterogeneous chemical reactions process. Table 5.5 shows the chemical reactions involved for homogeneous and heterogeneous process. The reaction model proposed by Badzioch and Hawksley [268] is considered for devolatilization. In this model, volatile production rate is largely dependent on the temperature history of the fuel particles and the kinetic rate constant. This phenomenon is taken into account using the Arrhenius equation [96]. After devolatilization, rest amount of coal and biomass particles are assumed to be char and ash. A steady reaction is occurred between the char and the surrounding gases. This char combustion process is modelled with a global power-law [27]. Selection of different rate constant such as pre-exponential factor ($A_v$) and activation energy ($E_v$) is important for proper combustion modelling of fuel particles. The kinetic rates for coal and straw particles in the present study are given in Table 5.6. A similar particulate phase (devolatilization and char oxidation) modelling was applied for both coal and straw particles combustion. The combustion of irregular shaped biomass char is quite complex. It is not only affected by the biomass composition, but also by the irregular shape and size of the particles. Gera [225] developed a model to consider the variation of particle shape of biomass (cylindrical to spherical) leading to vary the overall burning rate of the particles and hence a burning enhancement factor is proposed. A similar approach is used in the combustion modelling of cardoon particles co-fired with coal in a tangentially-fired furnace [92]. However, Yin [89] neglected the non-spherical
properties of the particle due to low char fraction and hence used the diffusion rate constant model without any enhancement factor. In this study, the effect of non-sphericity for the straw particles is taken into account in the particulate phase modelling by using the effect of variation of actual surface area of the particle to that of the spherical equivalent [59, 86].

**Table 5.5:** Chemical reactions for homogeneous (1) and heterogeneous (2) processes

<table>
<thead>
<tr>
<th>Order</th>
<th>Process</th>
<th>Chemical reactions</th>
<th>ΔH</th>
</tr>
</thead>
<tbody>
<tr>
<td>One-step</td>
<td>(1)</td>
<td>CH₄ + 2O₂ → CO₂ + 2H₂O + Heat</td>
<td>802310</td>
</tr>
<tr>
<td></td>
<td>(2)</td>
<td>C₉char + O₂ → CO₂ + Heat</td>
<td>393520</td>
</tr>
<tr>
<td>Two-step</td>
<td>(1)</td>
<td>CH₄ + 3/2O₂ → CO + 2H₂O + Heat</td>
<td>307880</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CO + .5O₂ ⇌ CO₂</td>
<td>1110190</td>
</tr>
<tr>
<td></td>
<td>(2)</td>
<td>C₉char + .5O₂ → CO + Heat</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CO + 1/2O₂ ⇌ CO₂</td>
<td>1110190</td>
</tr>
<tr>
<td>Three-step</td>
<td>(1)</td>
<td>CH₄ + O₂ → CO + H₂ + H₂O + Heat</td>
<td>549710</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CO + H₂O ⇌ CO₂ + H₂</td>
<td>868360</td>
</tr>
<tr>
<td></td>
<td>(2)</td>
<td>O₂ + 2H₂ ⇌ 2H₂O</td>
<td>483660</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C₉char + .5O₂ → CO + Heat</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CO + H₂O → CO + H₂</td>
<td>172 464</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C₉char + CO₂ → 2CO</td>
<td>131 298</td>
</tr>
</tbody>
</table>

**Table 5.6:** Kinetic parameters for devolatilization (1) and char combustion (2) of selected fuels [87, 158].

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>Processes</th>
<th>Activation energy E (J/kmol)</th>
<th>Pre-exponential factor A (1/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>(1)</td>
<td>1.559x10⁸</td>
<td>4.68x10¹¹</td>
</tr>
<tr>
<td></td>
<td>(2)</td>
<td>1.2x10⁸</td>
<td>9.48x10⁴</td>
</tr>
<tr>
<td>Straw</td>
<td>(1)</td>
<td>1.3800x10⁸</td>
<td>1.56x10⁶</td>
</tr>
<tr>
<td></td>
<td>(2)</td>
<td>1.3225x10⁸</td>
<td>1.7238x10⁷</td>
</tr>
</tbody>
</table>
Figure 5.3: Grid sensitivity analysis for only coal and straw combustion under (a). Air-firing and (b). Oxy-firing case.
For heat transfer modelling, discrete transfer radiation modelling (DTRM) is considered which is normally categorized under the WSGGM model. This model is important for gas radiation calculation and specific consideration is taken into account especially in the oxy-firing cases. In modelling, appropriate selection of the absorption co-efficient, surface discretisation and angular discretisation are important for accurate prediction of the radiation characteristics. The absorption model selected in this study is of great importance for the radiation calculation, particularly in the oxy-fuel combustion because of the higher percentage of concentration of CO$_2$. Hence, in this study, for air and oxy-fuel combustion, the absorption coefficient is set to 0.24 m$^{-1}$ and 0.31 m$^{-1}$ respectively. (See Section 3.3.5).

5.5. Grid Analysis and Validation of the Modelling

In order to reduce the computational time, a comprehensive grid independency test was conducted for the present modelling. A total of three grid sizes having 128,788, 257,576 and 386,364 cells are considered. A comprehensive analysis is presented in Figure 5.3. The figure shows the grid sensitivity test for only coal and straw combustion under air and oxy firing cases. It can be concluded that the grid size having 257,576 cells is optimum for further investigation with minimum computational time.

This numerical study is validated by comparing the predicted temperature data with the experimental data given in Ref. [324]. For the validation, only coal combustion is chosen under air-firing and oxy-fuel (OF30%) conditions. This will build up confidence for further modelling. Temperature profile data were compared with the measured data at a position through port 2 and port 4. It is seen in Figure 5.1 that Port 2 and port 4 are located approximately 123 mm and 398 mm from the burner end respectively. Figure 5.4 represents the comparison.
of the temperature mapping of the gas phase at the chosen conditions (air and OF-30% oxy-fuel) between numerical prediction and experimental measurement in order to validate the code. It is seen from the figures that near the furnace wall, comparatively lower temperatures were observed for both the cases.

For oxy-fuel case, slightly higher temperatures are predicted compared to air-firing in port-2. While comparing numerical to experimental data, variation is below 10% error range. In port-4, oxy-fuel flue gas maintains a higher average temperature. This is owing to a permutation of the higher heat capacity of CO₂. Compared to the experimental data, a close temperature profile is observed throughout the port for the simulated result.

5.6. Results and Discussion

The objective of this study is to illustrate the impact on the combustion characteristics including flame temperature, burnout, and emissions when pure biomass (straw) and blends of coal and biomass are combusted in air and oxy-fuel atmospheres. All modelling in the following have been performed with equal thermal input (30 kW). In order to set a reference oxy-fuel case, a comprehensive analysis is conducted using three different oxidizer (O₂) concentrations. Oxy-fuel combustion can be applied to biomass as well as coal and the use of CO₂ neutral fuels induces the potential of achieving an overall negative CO₂ emission from the power plant. Following section will demonstrate the investigated outcome of the present computational study.
Figure 5.4: Comparison of predicted radial gas-phase temperature profiles with experimental data [324] between air and oxy-fuel cases, (a). Port-2, (b). Port-4.
5.6.1. Differences in Air to Oxy-fuel Combustion Environment

Variation of combustion environment plays significant role in the performance of power plant output. When transforming air to oxy-fuel environment, the difference can be observed in terms of flow variations, species concentration. This study will distinguish among the various cases considered. This section will investigate the differences in the combustion process between air and oxy-fuel combustion cases. Matching air to oxy-fuel combustion flame temperature is important for the purpose of retrofitting. Three different oxy-fuel cases such as OF25% (25% \( \text{O}_2 \) and 75%\( \text{CO}_2 \)), OF30% (30% \( \text{O}_2 \) and 70%\( \text{CO}_2 \)) and OF35% (35% \( \text{O}_2 \) and 65%\( \text{CO}_2 \)) were investigated with respect to flow and species distributions, flame temperature profiles, and emissions.

5.6.2. Flow distributions

Figure 5.5 represents the velocity distributions for air-firing and different oxy-fuel cases. For air and oxy-fuel cases, the primary oxidant flow is set at 20 vol% of the total oxidant flow conditions as given in Table 5.2. Secondary flow combines tangential and axial distributions based on swirl number and total oxidant flows. The burner is characterized with swirl stabilization in order to increase the mixing, stabilize the flame shape and to provide enough time to the oxidizers for complete burning of fuel. A constant swirl number of 1.8 is considered for all the cases. The primary oxidizer and the fuel particles are served into the boiler through primary inlet and swirled secondary oxidizers are fed through secondary air inlet as shown Figure 5.2. The axial flow distributions on the vertical plane of the boiler for all the cases are presented in Figure 5.5. Two recirculation zones are observed in the upper portion of the furnace. Internal recirculation is pointed out in the burner area where external recirculation is predicted in the upper portion near the wall of the furnace. It is also seen from the figure that the velocity is decreasing from with the increase of oxy-fuel cases. As the flow is decreased, so the residence time significantly
improves leading to better opportunity for combustion reaction, better ignition environment which will definitely enrich the flame temperature.

Figure 5.5: Axial flow (m/s) distribution for pure coal combustion under different combustion environment.

Figure 5.6: Oxygen mass fraction (%) distribution for pure coal combustion under different combustion environments.

Figure 5.7: Carbon dioxide mass fraction (%) distribution for pure coal combustion under different combustion environments.
5.6.3. Species distributions

Species such as O$_2$ and CO$_2$ mass fraction distributions for all the cases on the same plane as flow distributions is presented in Figure 5.6 and Figure 5.7 respectively. While transforming air to oxy-fuel combustion, the input of O$_2$ and CO$_2$ is significantly varied. According to Eddy Break-up (EBU) model, stream of O$_2$ in the reaction burner area contributes to the flame characteristics and the ignition environment. Based on the combustion environment, it is observed that for air-firing case and OF-25 case, a similar type of O$_2$ distribution is predicted. The distribution is comparatively wide due to higher oxidizer flow. In case of OF-30 and OF-35, significant increase in the concentration is observed compared to air and OF-25 cases. This can be explained that accessibility of O$_2$ is much enhanced and hence O$_2$ consumption is faster. This will lead to better ignition condition providing higher flame temperature in the reaction area. According to chemical possessions [280], CO$_2$ has advanced specific heat characteristics related to nitrogen (N$_2$). This property is accountable for absorbing more heat. That’s why; rise in CO$_2$ in oxy-fuel cases has noteworthy meaning in combustion environment compared to air fired case. It is predictable that in developed OF cases with enhanced O$_2$ level; the effect of CO$_2$ on the radiative property will reduce. The variation of CO$_2$ in the vertical plane in the upper portion of the furnace is presented in Figure 5.7 for all the cases.

5.6.4. Residence time for different combustion cases

In order to retrofit between air-firing to oxy-fuel combustion, it is important to consider the residence time of the fuel particles under different. An estimate of the average residence time of fuel particles in the reactor is determined and compared with the experimentally measured data. A similar analogy was considered to predict the residence time as a function of temperature profile and the flue gas flow rate. The average temperature (reactor centre values) in all the ports along the furnace is used for each combustion cases. Table 5.7 shows
the residence times predicted for all the cases. It is seen that average residence time increases with the increase of O₂ in oxy-fuel cases. An increase of about 33.4%, 42.0% and 60.0% in the average residence time of fuel particles in the chamber for air-firing, OF25%, OF30% and OF35% respectively. This can be justified with the lower flow rate of the oxidant as can be seen from Table 5.2. The increases in the residence time have direct impact on the combustion performance as well as the efficiency of the reactor during retrofitting a coal based power plant.

5.6.5. Matching of Air to Oxy-coal Combustion Using Flame Temperatures

In order to present the flame temperatures for different combustion environments, centreline temperature profiles were predicted for coal combustion in air firing and three different oxy-fuel firing environments as presented in Figure 5.8. Also, a comparison of the numerically predicted data with the experimental value is demonstrated. It is seen from the profile that the temperature is increasing with the increase of oxy-fuel cases. Though temperature profile deviates for different cases, but the peak temperature for air and all oxy-fuel flames are observed at a position of 0.25 m from the burner exit. Similar observation is noted in the experimental study. Comparatively higher flame temperature is predicted in the upper portion of the furnace compared to downstream section of the model. While comparing with the experimental data, a good agreement is found for all the cases. This study indicated that a similarity of flame profile could be attained with an inlet O₂ concentration between OF25% and OF30% cases. In OF-30%, comparatively higher temperature profile is observed compared to OF25%. Also, a critical analysis in the experimental study suggests that an inlet oxygen concentration of 27-28 % would yield a match between air-firing case and different oxy-fuel cases. Hence,
based on the numerical possibility and experimental suggestions, OF30% was selected as the reference oxy-fuel case for further study.

**Table 5.7:** Predicted average residence time for different combustion environment

<table>
<thead>
<tr>
<th>Case</th>
<th>Oxidizer</th>
<th>Residence time, T (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>Air-firing</td>
<td>2.60</td>
</tr>
<tr>
<td>Case 2</td>
<td>25% O₂/CO₂</td>
<td>3.47</td>
</tr>
<tr>
<td>Case 3</td>
<td>30% O₂/CO₂</td>
<td>3.70</td>
</tr>
<tr>
<td>Case 4</td>
<td>35% O₂/CO₂</td>
<td>4.20</td>
</tr>
</tbody>
</table>

**Figure 5.8:** Comparison of temperature distribution along the reactor centreline for different combustion cases using only coal.
5.6.6. Temperature Mapping for Different Coal/Biomass Co-firing Cases

Co-firing coal with biomass is considered as a relatively easy way of reducing CO₂ emissions from fossil fuel fired power plants. However, the biomass share of the fuel blend is typically kept low utilized to reduce superheater corrosion risks. Based on the co-firing ratios of coal and biomass (straw) given in Table 5.3 and Table 5.4, simulations have been carried out for all the cases under air-firing and reference oxy-firing cases. A comparison of the temperature profile along the radial direction at different port for air firing case is presented in Figures 5.9-5.13. Near the burner, due to flame front, a temperature gradient is predicted. With further down the reactor, almost constant temperature profiles across the reactor predicted. Comparatively lower temperatures were found near the furnace wall. While comparing with the experimental data provided, the profiles in port 1 are only shown for one half of the reactor performed at positive values of radial direction and is generally seen to be significantly varied for only straw combustion. But the numerical data presented a symmetrical distribution from the furnace centreline. In order to allow for variation in the modelling and measurement, a 5% error bars are added for all the cases.
Figure 5.9: Comparison of temperature mapping for four different fuel compositions under air-firing case (port-1)

Figure 5.10: Comparison of temperature mapping for four different fuel compositions under air-firing case (port-2)
Figure 5.11: Comparison of temperature mapping for four different fuel compositions under air-firing case (port-3).

Figure 5.12: Comparison of temperature mapping for four different fuel compositions under air-firing case (port-4).
As the study considered four different fuel compositions, there is an obvious difference in fuel characteristics among 100% coal, 20 % and 50 % coal/straw blends, and 100% straw. Based on these, a variation is observed in the ignition behaviour, flame shape, and temperature profiles. Compared to coal, straw particles always possess higher volatile matters (VM) and less fixed carbon (FC) as can be seen from Table 5.1. Also the particle size of the straw is irregular and larger compared to coal used. This will play a significant role in the performance of the combustion. Figure 5.14 represents a comparison of the flame between experimentally recorded and numerically predicted. Typical visualization of experimental representation of flame temperature is taken from Ref. [324] where the flame is not axisymmetric due to the swirling motion of the oxidant, however typical qualitative flame distribution is compared with the CFD simulation.
Figure 5.14: Typical flame temperature comparison for different coal/straw ratios under air to oxy-firing cases.
The CFD visualization is shown at a position of 0.5 m from the burner exit. For different co-firing cases, distribution of flame temperature variation is observed for selected combustion cases. It was found that with the increase of straw contribution, peak flame temperature leads to a lower value. This can be explained on the basis of higher volatile content and lower heating value. With the increase of straw sharing, the volatile fraction increase. The dominant effect of the lower calorific value of straw depresses the effect of volatile content. Thus, the principal effect of the lower calorific value of straw is to lower the flame temperature. But, compared to the air-firing case, a distinct observation is predicted for selected oxy-fuel case (OF30%). The OF30% case provides better flow mixing compared to air-firing case providing presence of high concentration of O\textsubscript{2} at lower flow rate. That is why in oxy-fuel cases a comparatively higher flame temperature is observed. Also, the characteristic of heat capacity of CO\textsubscript{2} contributes to the flame emissive properties. When oxygen (O\textsubscript{2}) concentration is decreased, the higher heat capacity of CO\textsubscript{2} tends to keep the flame temperature comparatively low.

For the selected fuel ratios, a comparison of the reactor centre line temperature profiles under air and oxy-fuel cases were presented in Figure 5.15(a) and Figure 5.15(b) respectively. It is seen for both the cases that near the burner, temperature variation is not significant for increasing straw share in the fuel supply. This difference is increased along the reactor centre line position. The temperature difference among the four cases of fuel ratios under air-firing is significant. It is seen that 20% sharing of straw does not significantly change the temperature profile compared to 100% coal firing. Based on these two plots, a direct comparison of the flame temperature profiles for air to oxy-firing for different co-firing ratios were presented in Figure 5.16.
Figure 5.15: Comparison of centreline temperatures for different fuel ratios under air to oxy-firing cases: (a). Air-firing, (b). Oxy-firing
Figure 5.16: Variation of reactor centreline temperatures for coal to straw against air to oxy-fuel cases.

The oxy-fuel temperature profiles show comparatively higher peak flame temperature than air. Also, in each position the temperature is generally higher than air for all the fuel cases. The outcome of changing environments from air to oxy-fuel is noticeable for 100% straw combustion. This similarity is observed for coal and straw burning as a comparatively higher temperature is always found for reference oxy-firing case. It is also observed for the entire combustion environment that 100% coal always produces higher temperatures than blends in oxy-firing case. In the downstream section of the reactor, blends of the straw content seem to have an insignificant effect on temperature. Compared to the air combustion case, there is less difference between coal-containing fuels and pure straw in the oxy-fuel cases.
Figure 5.17: Comparison of CO concentrations in radial direction for combustion different coal/straw blend in oxy-fuel conditions (port-1)

Figure 5.18: Comparison of CO concentrations in radial direction for combustion different coal/straw blend in oxy-fuel conditions (port-2)
Figure 5.19: Comparison of CO concentrations in radial direction for combustion different coal/straw blend in oxy-fuel conditions (port-3)

Figure 5.20: Comparison of CO concentrations in radial direction for combustion different coal/straw blend in oxy-fuel conditions (port-4)
Figure 5.21: Comparison of CO concentrations in radial direction for combustion different coal/straw blend in oxy-fuel conditions (port-5)

5.6.7. Effects of CO for Different Co-firing Under Oxy-firing

Figures 5.17-5.21 display the radial summaries of CO concentration profiles through the ports (1 to 5) for the oxy-fuel case. It is expected that the burnout is improved for oxy-fuel combustion than when using air as oxidant. The difference between the two atmospheres seems to increase with increasing fuel straw share. This indicates the relatively higher importance of the combined effect of the higher inlet O$_2$ concentration, increased maximum flue gas temperature, and increased residence time during oxy-fuel combustion for the burnout of large straw char particles. It is illustrated that the change in CO profile is found with the change of fuel compositions. In the down side of the reactor, CO level is comparatively low. This can be explained with the availability of sufficient O$_2$ level. Accessibility of oxidizing O$_2$ level contributes to the transformation of CO to CO$_2$. In port 1, near the burner exit,
concentration of CO level is very low. For 100% coal combustion case, the concentration of CO is very close to zero in the distant port. In all the ports, higher level of CO is observed for 100% straw burning case. This is due to increasing importance of increased residence time on the burnout for increasing fuel straw share.

![Comparison of carbon burnout for different coal/straw sharing under air to oxy-fuel combustion.](image)

**Figure 5.22:** Comparison of carbon burnout for different coal/straw sharing under air to oxy-fuel combustion.

### 5.6.8. The Effects of Burnout for Different Fuel Ratios

Figure 5.22 shows the analysis results between calculated and predicted carbon burnout efficiency for each cases as function of the fuel straw share. Burnout is dependent on several factors such as particle size, combustion environment and residence time. For both combustion atmospheres increasing the fuel straw share leads to reduced burnout. It is evident that with the increase of biomass sharing, burnout is decreased in most of the cases. It can be described that with the increase of straw sharing, an increasing number of large straw particles are transported through the furnace without being burned. The reduced burnout is
due to an increased amount of straw char particles being transported through the furnace with limited conversion of the fixed carbon content. Similar finding have been observed in the experimental data. Comparatively, improved burnout under oxy-fuel firing conditions is observed compared to air combustion for different biomass sharing cases. The increase in burnout efficiency is due to improved combustion conditions which favour fuel particles.

5.6.9. **Heating Profiles for Different Sizes of Straw Particle**

Determination of the heating profile is important for proper combustion possibility of the fuel particles. In this study, three different sizes of straw particles were considered, i.e, 100 µm, 330 µm and 1000 µm. The energy balance equation used to determine the heating profile considering radiative and convective heat transfer is used for tracking the particles temperature is given in the following equation:

\[
m_p C_{p,p} \frac{dT_p}{dt} = \pi d_p^2 \left( h(T_g - T_p) + \epsilon_p \sigma(T_w^4 - T_p^4) \right)
\]

Equation (5.1)

\[
m_p = \frac{\pi}{6} d_p^3 \rho_p
\]

Equation (5.2)

\[h = \frac{Nu \lambda_g}{d_p}\]

Equation (5.3)

\[Nu = 2 + mRe_p^{0.5} Pr^{3.3}\]

Equation (5.4)

\[Re_p = \frac{\rho_g u_t d_p}{\mu_g}\]

Equation (5.5)

Figure 5.23 shows the heating profile for air-firing and oxy-fuel cases for selected straw particle sizes. The particle temperature along the furnace centreline is taken from numerical results. The different properties and boundary values for the determination of heating profile is given in Table 5.8. It is found that for different particle sizes, significant variation is observed in
heating profile along the reactor centreline. For the first two cases, maximum temperatures were reached very close to the burner exit. But for larger particles, an increased temperature gradient is predicted. Table 5.9 shows average particle velocities of the investigated particle sizes and their residence time within the furnace. This was predicted at the exit of the furnace. The results clarify the cases when with large straw particles combusted inside the furnace and comparatively lower burnout is observed since the residence time is very limited. Due to the smaller flue gas flow during oxy-fuel combustion the residence time is longer and hence the burnout should increase. The increase in the particle velocity of large particles compared to the smaller size is responsible for less residence time inside the furnace.

Table 5.8: Boundary data and properties values used for calculation of heating profile for different size of straw particles.

<table>
<thead>
<tr>
<th>$C_{p,v}$</th>
<th>$T_{p,v}$</th>
<th>$\varepsilon_p$</th>
<th>$\sigma_\varepsilon$</th>
<th>$T_w$</th>
<th>$P_r$</th>
<th>$P_r^*$</th>
<th>$\Lambda_{gr}$</th>
<th>$P_{gr}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>J/kg.K</td>
<td>K</td>
<td>W/m²K⁴</td>
<td>°C</td>
<td>kg/m³</td>
<td>W/m.K</td>
<td>kg/m³</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>298</td>
<td>0.85</td>
<td>5.57X10⁻⁸</td>
<td>1000</td>
<td>500</td>
<td>1</td>
<td>0.09</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Table 5.9: Predicted average particle velocity (m/s) and average residence time (s) of different size of straw particles in furnace.

<table>
<thead>
<tr>
<th>$D_v$ (µm)</th>
<th>$u_v$ (m/s)</th>
<th>$t_p$ (s)</th>
<th>$u_v$ (m/s)</th>
<th>$t_p$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Air-firing</td>
<td>Oxy-fuel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>0.05</td>
<td>2.42</td>
<td>0.05</td>
<td>3.25</td>
</tr>
<tr>
<td>330</td>
<td>0.59</td>
<td>1.38</td>
<td>0.61</td>
<td>1.58</td>
</tr>
<tr>
<td>1000</td>
<td>2.61</td>
<td>0.53</td>
<td>2.34</td>
<td>0.61</td>
</tr>
</tbody>
</table>
Figure 5.23: Heating profiles for straw particles of different size in the reference air and oxy-fuel atmospheres.
5.7. **Summary**

The objective of this work was to implement the developed co-firing model for the combustion of irregular shaped straw particles having larger aspect ratios under air to oxy-firing combustion environments in a small scale furnace. Three different oxy-fuel cases such as OF25%, OF30% and OF35% were investigated with respect to flow and species distributions, flame temperature profiles, and emissions. A critical analysis suggested that an inlet oxygen concentration of 30% would yield a match between air-firing case and oxy-fuel cases. The effect of fuel switching from coal to straw was evaluated by comparing the co-firing cases considered. It is seen that 20% sharing of straw does not significantly change the temperature profile compared to 100% coal firing. With the increase of straw contribution, flame temperature is decreased. The higher level of CO is observed for 100% straw burning case. This was due to increasing importance of increased residence time on the burnout for increasing fuel straw share. Improved burnout under oxy-fuel firing conditions was observed compared to air combustion for different biomass sharing cases. Also the heating profile considering different sizes of straw particles were predicted.
Overview: This chapter presents a 3D numerical study considering co-firing concepts in a 550MW tangentially fired furnace using a commercial CFD code AVL Fire ver.2009.2. Necessary subroutines were written and coupled with the code to account for chemical reactions, heat transfer, fluid and particle flow fields and turbulence. Due to irregularities of the biomass particle shape, a special drag effect was considered. Three different co-firing cases (20% biomass with 80% coal, 40% biomass with 60% coal and 60% biomass with 40% coal) were considered. All the co-firing cases were simulated under air-firing and three different oxy-firing cases (25% O₂/75% CO₂, 27% O₂/73% CO₂ and 29% O₂/71% CO₂). A level of confidence has been achieved by conducting a study on co-firing of biomass with coal in a 0.5MWth small scale furnace under air and oxy-fuel conditions. Similar findings have been observed in the present study which indicates the model can be used to aid in design and optimization of large-scale biomass co-firing under oxy-fuel conditions. This study enables the calculation of species transport and mixing phenomena and the simulation of ignition, combustion and emission formation in industrial furnace. Results were presented by the aerodynamics of burner flow, temperature distributions, gaseous emissions such as O₂ and CO₂ distributions etc. With the increase of biomass sharing, peak flame temperature reduced significantly. The dominant effect of the lower calorific value of biomass dampens the effect of volatile content contributing to lower temperature. Comparatively, improved burnout is observed for the improved oxy-fuel cases. But, the CFD model predicted a significant increase in unburned carbon in fly ash for the increase of biomass co-firing sharing. Overall, this study highlights the positive impact of changing the fuel ratio and combustion atmosphere on the boiler performance, underlining
that minor redesign may be necessary when converting to biomass co-firing under air and oxy-fuel conditions.

6.1. Introduction

Due to increasing demand of energy, it is necessary to find the ways to meet the crisis of energy considering global warming, pollutant emission etc. This can be achieved by using renewable energy sources, as these are CO$_2$ neutral. The principal means of mitigating the future energy crisis is expanding the use of renewable energy and is an approach to attain sustainable development in the world. Biomass fuels are carbon dioxide (CO$_2$)-neutral energy source [26]. According to Ref. [69], out of the 62 countries that produce electricity using biomass, USA leads with a dominating 26% of world production. It is followed by Germany at 15%, and Brazil and Japan both produce 7% of electricity of world production. Compared to these countries, the usage of biomass in Australia is at an early stage.

Direct combustion of biomass fuel is one of the most common methods similar to coal combustion in the existing technologies for utilizing biomass energy in industrial purposes. However, co-combustion of biomass with coal provides a significant option for mitigating power demand as biomass is considered as one of the energy source which can be used for mitigating emissions [25, 64-67]. The combustion of biomass is the most economical way to utilize renewable energy as it contributes over 97% of the world’s bio-energy production [68]. In recent years, a number of technologies have been developed to promote the continuous use of fossil fuels. The objectives of these strategies are to reduce emissions as well as to reduce fuel consumption [22, 55, 102, 330]. Among them, as oxy-fuel combustion system has been widely used as the most viable approach in a pulverized coal power plant [61, 289, 331, 332]. In last 10 years,
research has been oriented to considering oxy-fuel combustion technology not only by experimental work [60, 332-335] but also by theoretical studies including computer modelling [18, 96, 336, 337]. The outcomes of these studies were to investigate species concentration, temperatures, burnout, emissions and heat transfer etc.

Several experimental investigations including both laboratory/pilot and industrial scale facilities were conducted to demonstrate the importance of combustion of different biomass with coal [85, 91, 177, 191-194]. These studies were conducted to determine the ignition characteristics, emissions, and ash characteristics for blended fuel. A detailed investigation of co-firing of biomass with coal in a coal fired power generation system was given in Refs. [189, 190] from technical and environmental points of view. It was found that a high burnout up to 20% thermal input of biomass was obtained during co-firing of biomass with coal.

As biomass varies, based on their availability in respective area, different researchers considered various sources, straw is one of them [184, 187, 188]. It was found that an increase in the fraction of straw in the blend reduces NO and SO₂ emissions. Some authors considered the olive cake waste as an energy source [183, 186]. Cliffe [35] indicated that while comparing the combustion efficiency and CO emission with burning of 100% coal, it was found that 20% olive oil waste can be co-fired with coal in a designated fluidised bed type coal combustion furnace with a maximum efficiency drop of 5%. Municipal solid waste (MSW) [338, 339] were co-fired in several studies [178]. The outcomes indicate that within the 40% MSW fraction, combustion efficiency drop of up to 8%. Sewage sludge [179], Miscanthus [88] were also studied by several authors. Other work reports on emissions of hydrocarbon species from combustion of coal, sugar-cane bagasse, and blends thereof in a laboratory furnace [84, 180].
Several researchers considered rice husk as a co-combustion fuel, a by-product of the rice-milling process, one of the most potentially sustainable biomasses [181, 182, 185, 195]. During experiment, it was found that an operation range of 10-30% of biomass to coal ratio is the optimum range for minimum pollutant emissions. In Ref. [72], a detailed investigation of synergetic interaction of the inorganic elements of coal with woody biomass, cedar chips were conducted in a small scale furnace to determine the emission of micro level particles. Another research was conducted using saw dust with coal at FORTUM’s Naantali-3 power plant, concludes that can substitute 5-30% coal by biomass fuel [31].

Practical combustion always involves emissions. The species that evolves not only depend on the fuel but also depend on the combustion conditions, e.g. equivalence ratio, residence time, temperature, air supply, etc. Emissions coming from renewable fuels, like biomass, can be divided into two different groups: (1) emissions with origin from complete combustion and (2) emissions whose origin comes from incomplete combustion [54, 197-200]. As oxy-fuel combustion is a greenhouse gases abatement technology, co-combustion of biomass with coal under oxy-fuel condition were regarded as an substitute method to the CO$_2$ recycle method by several authors [126, 208-211]. Rubiera [126] analysed the effect of biomass co-firing with coal combustion using recycled flue gas and suggested that at O$_2$ of 30% or higher, better ignition was achieved and the combination of biomass with coal clearly improves the ignition performance.

CFD is an approach for modelling combustion of biomass particles is a significant challenge. CFD modelling of biomass co-combustion with appropriate turbulent model, precise particle trajectories model and chemical reactions modelling on different boilers are demonstrated in the literature. There have been a limited number of numerical analyses of biomass co-
combustion using CFD models including all the stages of the combustion[80]. CFD modelling made for coal combustion has been modified to apply to biomass co-combustion. Only a few CFD attempts in biomass co-combustion in boilers and furnaces are found in literature in small or large scale [36, 52, 71, 80, 81, 197, 209, 227, 233, 234]. Several small scale investigations are attempted for the co combustion of biomass using CFD. Williams [82] demonstrated that co-combustion modelling of biomass with coal leading to the reduction of CO₂. In most of the studies, attention is focused on the combustion of the larger and irregular biomass particles. Several simplified assumptions were considered which can be further investigated. For the biomass particles having larger diameter, a computational sub-model is developed by Gubba [216] in order to determine the influence of particle shape of biomass in coal/biomass co-firing. Few researchers’ attempts to simulate the 3D large scale tangentially fired power generation plants using CFD [31, 37, 73, 83, 92, 229, 235, 236].

From the literature it was found, that the diverse numerical as well as experimental studies of biomass co-firing have shown possibilities to investigate different issues of the systems in industrial furnaces. It is essential to model the co-combustion phenomena in order to determine the potential difficulties that may arise due to biomass co-combustion and to mitigate potential negative effects of biomass fuels, including lower efficiency due to lower burnout. A CFD study to scrutinize the co-firing of coal and larger having irregular shaped biomass particles burnout is vital. Non-sphericity of biomass particles in modelling of combustion is a challenging task in CFD. Hence, the determination of this study is to study the ignition behaviour of the biomass co-firing with coal using CFD modelling. In this study, a tangentially fired 550 MW boiler [340] has been considered for modelling of co-firing of biomass with Victorian Brown coal. Previously, few numerical works [14, 100] on this large scale furnace have been conducted for only brown coal combustion under
different operating conditions. Despite of numerous advantages of Victorian brown coal in power plant, a sharing of biomass may provide a significant support in power generation. Hence, the objective of this investigation is to model the co-firing concept of biomass with brown coal in an industrial scale furnace under several oxy-fuel cases. Oxy-fuel combustion tactics that was conducted experimentally in the Chalmers’ lab-scale furnace [341] and numerically by Al-Abbas [95, 96], has been chosen in the present study for co-firing. The confidence of this selection was developed in the author’s previous work [14, 62, 100, 314]. Also, the confidence of co-firing modelling is applied based on the small scale study given in Ref [59, 74]. The CFD code AVL Fire 2009.2, allowing for the necessary user-defined sub-model routines.

**Table 6.1:** Furnace details and burner specifications.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Furnace details</strong></td>
<td></td>
</tr>
<tr>
<td>Unit name</td>
<td>Unit 1 at Loy Yang A</td>
</tr>
<tr>
<td>Location</td>
<td>Latrobe Valley, Victoria, Australia</td>
</tr>
<tr>
<td>Orientation</td>
<td>Tangentially-fired</td>
</tr>
<tr>
<td>Capacity</td>
<td>550MW</td>
</tr>
<tr>
<td>Unit production</td>
<td>430 kg/s of steam</td>
</tr>
<tr>
<td>Operating condition</td>
<td>16.8 MPa, 540°C</td>
</tr>
<tr>
<td>Dimensions</td>
<td>98.84 m (l) x17.82 m (w) x17.82 m (h)</td>
</tr>
<tr>
<td>Fuel delivery system</td>
<td>Centrifugal separation</td>
</tr>
<tr>
<td><strong>Burner details</strong></td>
<td></td>
</tr>
<tr>
<td>No of mill duct system</td>
<td>08</td>
</tr>
<tr>
<td>No of burner in each duct</td>
<td>06 (Inert + Main)</td>
</tr>
<tr>
<td>Total no of burner</td>
<td>48 (18 out of service)</td>
</tr>
<tr>
<td>No. of Inert Burner (IB)</td>
<td>03</td>
</tr>
<tr>
<td></td>
<td>i. Upper inert (UIB)</td>
</tr>
<tr>
<td></td>
<td>ii. Intermediate inert (IIB)</td>
</tr>
<tr>
<td></td>
<td>iii. Lower inert (LIB)</td>
</tr>
</tbody>
</table>
No. of Main Burner (MB) 03
i. Upper main (UMB)
ii. Intermediate main (IMB)
iii. Lower main (LMB)

No. of secondary air Duct (SAD) in inert burner (IB) 04
i. Upper inert (UISAD)
ii. Upper intermediate inert (UIISAD)
iii. Lower intermediate inert (LIISAD)
iv. Lower inert (LISAD)

No. of secondary air Duct (SAD) in main burner (MB) 06
i. Upper main (UMSAD-1& 2)
ii. Intermediate main (IMSAD-1& 2)
iii. Lower main (LMSAD-1& 2)
v. Intermediate core (ICSAD)
vi. Upper core (UCSAD)
v. Middle core (MCSAD)
v. Lower core (LCSAD)

6.2. Computational Details

6.2.1. Furnace and Burner Configuration

In the present study, a 550MWe furnace located in Australia was considered for the investigation of co-firing concept by computational fluid dynamics (CFD) study. The details including dimensions, maximum operating conditions, unit productions of the utility furnace is summarised in Table 6.1. The furnace considered in this study includes furnace hopper, several burners, water wall, hot gas off-take (HGOT) port, several accessories like, economiser, superheater, reheater and a bifurcation to air heater. The schematic diagram of the computational model is presented in Figure 6.1. There are total eight mill-duct systems in four sides of the furnace. In this study, only five mills (1, 2, 5, 6, and
8 mills) are considered in operation and the rest are out of service (3, 4, and 7 mills) in order to maintain the similar operating conditions as in Ref. [100]. These duct system consists of several burners, secondary air duct (SAD) system and hot gas off-take (HGOT) port. There are mainly two types of burner used, i.e.; inert burner (IB) and main burner (MB). Each burner is surrounded by several oxidizer flow systems. The arrangements and positions of these burners are based on the original power plant design data. Details of the burner specifications are documented in Table 6.1. The position of different burners and secondary air duct (SAD) system and the orientations are presented in Figure 6.2. Figure 6.2 shows that each burner ports 1, 3, 5, and 7 were inclined by 24° while each of the remaining burner ports 2, 4, 6, and 8 were inclined by 30° with the perpendicular line to the furnace face. This configuration of the burner set up was mostly used in this type of tangentially-fired furnace in order to improve flame stability inside the furnace. It is seen from the Figure 6.2 that secondary air duct (SAD) system were designed with inert burner (IB) in such a way to improve the combustion characteristics. Similar mechanism is applied for the design of main burner (MB). For improved air flow distribution in the furnace central zone of the main burner, a number of core air ducts are attached.
Figure 6.1: Schematic view of the computational model used in this study.
Figure 6.2: (a). Combination of different burners and secondary air duct systems, (b). layout and orientation of different burners and HGOTs ports.
Table 6.2: Different combustion cases considered for co-firing concept.

<table>
<thead>
<tr>
<th>Co-firing scenarios</th>
<th>Air Firing (AF)</th>
<th>Oxy-firing (OF)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Case-A</td>
<td>Case-B</td>
</tr>
<tr>
<td></td>
<td>23% O₂+77% N₂</td>
<td>25% O₂+75% CO₂</td>
</tr>
<tr>
<td>Case-1</td>
<td>Case-A1</td>
<td>Case-B1</td>
</tr>
<tr>
<td>(80% Coal+20% Biomass)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case-2</td>
<td>Case-A2</td>
<td>Case-B2</td>
</tr>
<tr>
<td>(60% Coal+40% Biomass)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case-3</td>
<td>Case-A3</td>
<td>Case-B3</td>
</tr>
<tr>
<td>(40% Coal+60% Biomass)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
6.2.2. Cases Considered for CFD Modelling

In the present study, three different co-firing ratios have been considered to investigate the thermal performance of the boiler under different combustion cases. Three co-firing cases are: Case-1 (coal 80% and biomass 20%), Case-2 (coal 60% and biomass 40%) and Case-3 (coal 40% and biomass 60%). As mentioned earlier, this study is based on the previous numerical work [14, 100] of coal combustion modelling. The chemical and physical set up of the furnace and operating conditions of Ref. [100] were entirely taken from furnace station data [340]. But in this study, instead of only coal, biomass fuel is also combined with the coal as presented in Table 6.2. Regarding combustion environment, similar to Al Abbas [14, 100], a total of four combustion environment, air-firing (AF) (case A) and three different oxy-fuel (OF) combustion scenarios (Case B, C and D) have been considered. The oxy-fuel cases are OF25 (case B), OF27 (case C) and OF29 (case D). Each of the co-firing cases (cases 1-3) is simulated under all combustion environments. The compositions of coal biomass ratio for selected cases and combustion environment are summarized in Table 6.2. The selection of different combustion environment is based on author’s previous studies [95, 96, 230].

6.2.3. Fuel Properties and Distribution

The biomass fuel particles are co-fired with Victorian Brown coal at different ratios. The proximate and ultimate data of the coal and biomass particles used in the study is summarized in Table 6.3. In order to attain combustion stability, about 82% of the total fuel particles are introduced through main burner (MB) and 66% of the gases are passed through the inert burner (IB). The distribution of fuel particles are based on the selected co-firing ratios considered in this study. The stoichiometric ratio (k) of the oxidizers to fuel equals to 1.18 was maintained for all combustion cases investigated. The distribution ratios of fuel
particles and flow rates for different cases are presented in Table 6.4. In the present study, coal particle is assumed to be spherical in size. The coal particles are in the range of 0.01-1.5mm. In the code, coal particle distributions are inserted as Rosin-Rammler distribution (RRD) through different burner such as UIB, IIB, LIB, UMB, IMB and LMB with the prescribed distribution ratios given in and flow rates as presented. Details about Rosin-Rammler distribution is given in Ref. [100]. Biomass particle are assumed to be irregular in shape. Due to complexity in shape, controlling the drag coefficient is important. This phenomenon is considered based on the work given in Refs. [59, 74]. Biomass particles were in the range of 0.09-3.0 mm, and length to diameter ratio was assumed as 10:1 based on the similar study given in Ref. [286].

**Table 6.3**: Fuel properties used in this study.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Coal</th>
<th>Biomass</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Proximate analysis</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volatile matter, % wt (db)</td>
<td>50.5</td>
<td>74.7</td>
</tr>
<tr>
<td>Ash content, % wt (db)</td>
<td>1.70</td>
<td>5.87</td>
</tr>
<tr>
<td>Fixed Carbon, % wt (db)</td>
<td>47.8</td>
<td>19.4</td>
</tr>
<tr>
<td>Moisture, % wt (ar)</td>
<td>62.0</td>
<td>2.80</td>
</tr>
<tr>
<td><strong>Ultimate analysis</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C content, % wt (ar)</td>
<td>67.7</td>
<td>52.3</td>
</tr>
<tr>
<td>H content, % wt (ar)</td>
<td>4.63</td>
<td>6.40</td>
</tr>
<tr>
<td>N content, % wt (ar)</td>
<td>0.52</td>
<td>0.20</td>
</tr>
<tr>
<td>S content, % wt (ar)</td>
<td>0.30</td>
<td>0.00</td>
</tr>
<tr>
<td>O content, % wt (ar)</td>
<td>24.9</td>
<td>41.1</td>
</tr>
<tr>
<td>GCV, MJ/kg</td>
<td>27.6</td>
<td>18.9</td>
</tr>
</tbody>
</table>
**Table 6.4:** The flow rates and distribution ratios for coal and biomass at different inlets of the burner for different co-firing ratios

<table>
<thead>
<tr>
<th>Burner</th>
<th>Case (A1, B1, C1, D1)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>flow rates, kg/s</td>
<td>Distribution ratio, %</td>
</tr>
<tr>
<td></td>
<td>Coal</td>
<td>Biomass</td>
</tr>
<tr>
<td>UIB</td>
<td>0.744</td>
<td>0.186</td>
</tr>
<tr>
<td>IIB</td>
<td>0.432</td>
<td>0.108</td>
</tr>
<tr>
<td>LIB</td>
<td>1.256</td>
<td>0.314</td>
</tr>
<tr>
<td>UMB</td>
<td>3.856</td>
<td>0.964</td>
</tr>
<tr>
<td>IMB</td>
<td>2.224</td>
<td>0.556</td>
</tr>
<tr>
<td>LMB</td>
<td>4.496</td>
<td>1.124</td>
</tr>
<tr>
<td>Total</td>
<td>13.008</td>
<td>3.252</td>
</tr>
</tbody>
</table>
Table 6.5: The mass flow rates and feed gas compositions through different burners for air firing and oxy-firing combustion in different co-firing ratios.

(a) Species concentrations distribution for case A and B

<table>
<thead>
<tr>
<th>Burner</th>
<th>Flow condition</th>
<th>Species concentrations for different combustion cases, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Distribution, %</td>
<td>Flow (kg/s)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UIB</td>
<td>22.1</td>
<td>18.71</td>
</tr>
<tr>
<td>IIB</td>
<td>21.5</td>
<td>18.22</td>
</tr>
<tr>
<td>LIB</td>
<td>21.5</td>
<td>18.19</td>
</tr>
<tr>
<td>UMB</td>
<td>12.2</td>
<td>10.30</td>
</tr>
<tr>
<td>IMB</td>
<td>11.1</td>
<td>9.340</td>
</tr>
<tr>
<td>LMB</td>
<td>11.6</td>
<td>9.800</td>
</tr>
</tbody>
</table>
(b). Species concentrations distribution for case C and D

<table>
<thead>
<tr>
<th>Burner</th>
<th>Flow condition</th>
<th>Species concentrations for different combustion cases, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flow (kg/s)</td>
<td>Case C (C1, C2, C3)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>O₂</td>
</tr>
<tr>
<td>UIB</td>
<td>22.1</td>
<td>18.71</td>
</tr>
<tr>
<td>IIB</td>
<td>21.5</td>
<td>18.22</td>
</tr>
<tr>
<td>LIB</td>
<td>21.5</td>
<td>18.19</td>
</tr>
<tr>
<td>UMB</td>
<td>12.2</td>
<td>10.30</td>
</tr>
<tr>
<td>IMB</td>
<td>11.1</td>
<td>9.340</td>
</tr>
<tr>
<td>LMB</td>
<td>11.6</td>
<td>9.800</td>
</tr>
</tbody>
</table>
Table 6.6: The mass flow rates and feed gas compositions through different secondary air ducts (SAD) for air firing and oxy-firing combustion in different co-firing ratios.

<table>
<thead>
<tr>
<th>SAD</th>
<th>Distribution</th>
<th>Case A (A1, A2, A3)</th>
<th>Case B (B1, B2, B3)</th>
<th>Case C (C1, C2, C3)</th>
<th>Case D (D1, D2, D3)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n %</td>
<td>Flow (kg/s)</td>
<td>Compositions (%)</td>
<td>Flow (kg/s)</td>
<td>Compositions (%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>O₂</td>
<td>N₂</td>
<td></td>
</tr>
<tr>
<td>UISAD</td>
<td>5.0</td>
<td>6.89</td>
<td>23</td>
<td>77</td>
<td>5.71</td>
</tr>
<tr>
<td>UIISAD</td>
<td>5.0</td>
<td>6.89</td>
<td>23</td>
<td>77</td>
<td>5.71</td>
</tr>
<tr>
<td>LIISAD</td>
<td>5.0</td>
<td>6.89</td>
<td>23</td>
<td>77</td>
<td>5.71</td>
</tr>
<tr>
<td>LISAD</td>
<td>5.0</td>
<td>6.89</td>
<td>23</td>
<td>77</td>
<td>5.71</td>
</tr>
<tr>
<td>UMSAD</td>
<td>20</td>
<td>27.55</td>
<td>23</td>
<td>77</td>
<td>22.87</td>
</tr>
<tr>
<td>UCSAD</td>
<td>6.67</td>
<td>9.19</td>
<td>23</td>
<td>77</td>
<td>7.62</td>
</tr>
<tr>
<td>IMSAD</td>
<td>20</td>
<td>27.55</td>
<td>23</td>
<td>77</td>
<td>22.87</td>
</tr>
<tr>
<td>ICSAD</td>
<td>6.67</td>
<td>9.19</td>
<td>2</td>
<td>77</td>
<td>7.62</td>
</tr>
<tr>
<td>LMSAD</td>
<td>20</td>
<td>27.55</td>
<td>23</td>
<td>77</td>
<td>22.87</td>
</tr>
<tr>
<td>LCSAD</td>
<td>6.67</td>
<td>9.19</td>
<td>23</td>
<td>77</td>
<td>7.62</td>
</tr>
</tbody>
</table>
6.2.4. Applied Boundary Conditions

It is important to set up the proper boundary condition in modelling co-combustion of biomass with coal by controlling the aerodynamics of irregular shaped fuel particles of biomass under different operating conditions. Accurate modelling of co-firing in tangentially fired furnace is largely dependent on the accurate setup of the required boundary conditions. The chemical and physical set up of the furnace and operating conditions were entirely based on the station data [340] for coal combustion under air-firing case only. In order to conduct the modelling, for different combustion environment were considered (shown in Table 6.2). In all the cases, gas compositions were based on the experiment in the Chalmers’ lab-scale furnace [341] and numerical work by Al-Abbas [95, 96]. In this study, the computational model is characterized into three main sections such as inlet of various firing group system, vertical wall of the furnace and the exit of the facility. Each firing group consists of various burners and secondary air ducts (as shown in Figure 6.2). The fuel (coal and biomass), oxidizers, inert flue gas, water vapour, air, or/and O\textsubscript{2}/CO\textsubscript{2} are supplied to the boiler through mill-duct systems to the prescribed incoming ports mounted on the furnace wall.

The inlet boundary condition of the present modelling is based on the outlet condition of the study in Ref. [342] which was used in mill duct system of the Loy Yang power station. In supplying the fuel and oxidizer through burner and secondary air duct systems, a constant fuel/oxidizer ratio is maintained. In each burner, the fuel and gas were injected at a mass flow of 16.26 kg/s and 84.56 kg/s respectively. The secondary air was made-up to be supplied through each mill-duct group uniformly. The amount of air flow through the secondary air duct (SAD) system was set to 120.79 kg/s. The fuel particles were introduced based on the different co-firing ratio as shown in Table 6.2. With the variation of sharing of biomass particles, coal particles were introduced maintaining the co-
firing ratios as summarised in Table 6.4. In the study of Al-Abbas [100], fine-tuned gas mixture has been assumed in mixing after the mill. Similar approach was considered in this study. The mass flow rates and feed gas compositions (mainly includes O₂, N₂, CO₂, H₂O) through different burners for air firing (AF) (Cases A1, A2 and A3) and oxy-firing (OF) (B1, B2, B3, C1, C2, C3, D1, D2, D3) combustion cases considered in this study are presented in Table 6.5. The mass flow rates and feed gas compositions through different secondary air ducts (SAD) systems for the similar cases are presented in Table 6.6. The temperature of the burners and the secondary air duct (SAD) systems were set to 397 K and 473 K respectively. In industrial furnace, leakage of air is an issue in duct system, firing system and hopper ash removal system. These effects were considered according to similar numerical study in Refs. [16, 100, 284].

In order to apply the accurate wall boundary condition, available experimental data of the furnace is taken into account for proper modelling. Major wall boundaries include furnace zone, water tube, convection zone, and round duct wall as shown in Figure 6.1. Prescribed wall conditions of these zones are applied. Different convection zone such as reheater, economiser, superheater are set to the values of heat absorption of 121.98 MW, 100.0 MW and 115.75 MW respectively though a user defined sub coding. More details about the wall boundary data are given in Ref. [100]. The furnace in Ref. [100] was thermally balanced as a whole, based on measurements of a conventional combustion conditions. However, in the present study of co-firing concept, similar type of wall boundary data was chosen. Generally, for the gas phase modelling, non-slip boundary condition (u, v, and w = 0) is applied for the wall surface. The emissivity and temperature of the wall surfaces are set to be 0.71 and 973 K [92] respectively. In particle wall interaction modelling, total elastic (ideal) reflection of particles on wall is assumed. Hybrid wall treatment is applied considering
standard wall function heat transfer wall model to confirm a steady transformation between laminar to turbulent quantities of the boundary layers.

There are two outlets of the computational furnace. These are: bifurcation port, and hot gas off takes (HGOTs). For all the cases considered, a zero gradient were applied in bifurcation port. The predicted outcome in the bifurcation port is assumed as the inlet to the air heaters. The calculation at the bifurcation port predicts the flue gas outlet temperature, the efficiency of the boiler, and also the temperature distribution in it. However, air heating section is not modelled in the present computation. On the other hand, an outward mass flow of 61.0 kg/s was applied for all the active HGOTs port.

Initial conditions of the furnace are assumed as follows: density, 1.206 kg/m³, temperature, 293 K, turbulent kinetic energy 0.001 m²/s², turbulent dissipation rate 0.00519615 m²/s³. In all the combustion cases, for the main burner (MB), inert burner (IB) and for all the secondary air duct inlets, turbulent kinetic energy is set to 0.001 m²/s². But its dissipation rate is changed with the length scale. For inert burner (IB), main burner (MB) and all SAD systems, a turbulent dissipation rate of 4.36 x 10⁻⁵, 5.48 x 10⁻⁵ and 1.58 x 10⁻⁴ m²/s³ were used respectively.

6.3. Mathematical Model Used

Modelling of co-firing of pulverised Victorian brown coal with different sharing of biomass under different operating conditions were conducted by a commercial CFD code AVL Fire version 2009.2. In order to predict the temperature fields, flow characteristics, species generation and heat transfer performance, user defined subroutines were developed and coupled with the code for the modelling of devolatilization and char oxidation, controlling the aerodynamics of irregular shaped biomass particles and convective and
radiative heat transfer calculation. Different models such as gas flow modelling, particle flow modelling, chemical reaction modelling and radiation heat transfer modelling used in this study are discussed in brief in the following section.

Gas flow modelling: In this study, fluid and particle flow are described by the Eulerian/Lagrangian approach. 3D non-steady state Eulerian partial differential conservation equations (PDE’s) are considered for gas phase [325-328]. The heat transfer, particle trajectories, turbulence are coupled through the source term in the form of transport equation given in Ref. [263] (See Section 3.3.1).

Particle flow modelling: In this study, Eddy Breakup (EBU) model, a typical mixed-is-burnt combustion model is applied for all the combustion modelling cases. This model determines whether O\textsubscript{2}/fuel is in limiting condition or not. The detail of this model is given in Ref. [60]. The Discrete Droplet Method (DDM) is widely used method for particulate phase modelling including momentum exchange, heat and mass transfer phenomena. (See Section 3.3.2).

Drag force has significant effects on the particle trajectories which is largely dependent on drag coefficient. In order to consider proper particle aerodynamics, selection of accurate value of the drag coefficient is important which depend on associated particle size and the Reynolds number of the particle. From the various formulations in literature for the drag coefficient of a single sphere, AVL Fire 2009.2 uses the formulation for spherical shaped particle from Schiller and Naumann [219]. But for irregular shaped particles, the formulations for drag coefficients can be implemented and can be activated as the user drag in the graphical user interface (GUI). In this study, Biomass particle are considered as irregular shaped and have a large aspect ratio. To account for the abnormality of the shape from spherical, a particle shape factor \( f \) was employed. The shape suggestively influences the flow behaviour of the
particles. The definition of shape factor is given in Ref. [59]. As suggested in literature, for irregular shaped biomass particle, correlation of Haider and Levenspiel given in Ref. [218] is considered. The formulation used in the present study is given in Table 6.7.

Reactions modelling: In the present study, a three-step homogeneous and heterogeneous chemical reactions have been considered for the modelling of devolatilization and char oxidation processes respectively. In devolatilization, reaction model proposed by Badzioch and Hawksley [268] is considered where the rate of volatile production depends on the temperature history of the particle and the rate constant. It is observed that one-step reaction scheme cannot precisely calculate the formation of different gas species and showed some inaccuracies in the simulated result compared with the experiments [95, 96]. A comparative study of one step, two step and three steps reactions mechanism were evaluated in Ref. [95] and it was concluded that a three steps reaction mechanism is appropriate in modelling combustion. These chemical reactions are applicable both for air firing and oxy firing conditions. Due to increasing amount of CO$_2$ and H$_2$O concentrations in the flue gas, three steps chemical reactions are appropriate in oxy fuel combustion modelling. In this study, the char combustion is modelled with global power-law where diffusion of O$_2$ is responsible for the oxidation rate of char particle. Similar to devolatilization, three-step chemical reaction for char oxidation is considered. Three-step chemical reactions for homogeneous and heterogeneous processes are given in Table 6.7. Few researchers [16, 98] reported on the importance of Boudouard reaction in oxy-fuel combustion modelling and were considered in the present study. The value of the Arrhenius rate constants such as pre-exponential factor (A$_v$) and activation energy (E$_v$) is dependent on the proximate and ultimate approximation of the fuel data [70]. Selection of these
reaction factors is an important issue for modelling proper devolatilization. The used values of these constants are given in Table 7. (See Section 5.4)

Radiation modelling: The discrete transfer radiation method (DTRM) given in Ref. [272] is considered in this study has shown to be a very appropriate method for general radiation predictions which is easily embedded in overall CFD procedure. Fluid radiative properties’ modelling is uncoupled from DTRM and, depending on the problem; various models can be used for this. In the current study, the weighted sum of gray gases model (WSGGM) is adopted for absorption coefficient modelling in non-homogenous participating media. WSGGM model is very useful for the calculation of gas radiation especially in oxy-firing cases, where CO$_2$ and H$_2$O present in high concentration [129, 289]. It is also possible to define a constant absorption coefficient or to consider the medium as transparent for radiation and to calculate the surface-to-surface radiation only. (See Section 3.3.5).

6.4. Numerical Procedure

6.4.1. Description of the Model

The present combustion modelling is carried out using a commercial computational fluid dynamics code AVL Fire ver.2009.2 coupled with the user defined sub routines. The computational model, its geometry and dimensions were selected from previous studies of [100] similar to the power plant data given in [340]. As the code follows the finite volume approach, a standard convergence criterion of residuals $10^{-04}$ was considered for all the variables in solving 3-D equations of combustion, heat and mass transfer, and turbulent flow under transient mode. SIMPLE algorithm, the discrete form of the continuity equation is used to update the pressure and velocity fields so that the
velocity components obtained from the solution of momentum equations satisfy
the continuity equation. Varying time steps were applied starting from 0.0005 s
to attain a stability of the flame temperature. Time steps were further increased
to 0.0025 s up to the run of 48,000 time steps where quasi steady state is
achieved. The numerical results were averaged over the next 10,000 time-steps.
The total number of particles per second considered in this study was 50,000
which were equally distributed to each mill duct system. The distribution of
coal and biomass particles in each inlet ports was based on the co-firing ratio (as
shown in Table 6.4).

<table>
<thead>
<tr>
<th>Table 6.7: Main Models and parameters used in the simulation.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Different model used and related parameters</td>
</tr>
<tr>
<td>1. <strong>Gas phase model:</strong> Eulerian partial differential equations</td>
</tr>
<tr>
<td>2. <strong>Particulate phase model:</strong> Discrete Droplet Method (DDM)</td>
</tr>
<tr>
<td>3. <strong>Turbulence:</strong> k-ε turbulence model</td>
</tr>
<tr>
<td>4. <strong>Radiation:</strong> Discrete transfer radiation method (DTRM)</td>
</tr>
<tr>
<td>5. Particle aerodynamic</td>
</tr>
<tr>
<td>For coal (spherical particle)</td>
</tr>
</tbody>
</table>
| \( C_D = \begin{cases} 
\frac{24}{Re} (1 + 0.15Re^{0.687}) & \text{Re} < 10^3 \\
0.44 & \text{Re} \geq 10^3 
\end{cases} \) |
| For biomass (Irregular shaped particle)                       |
| \( C_D = \left(\frac{24}{Re} \right) (1 + b_1Re^{b_2}) + \frac{b_3Re}{b_4+Re} \) |
| \( b_1 = \exp\left(2.3288 - 6.4581f + 2.4486f^2\right) \) |
| \( b_2 = (0.0964 + 0.5565f) \) |
| \( b_3 = \exp\left(4.905 - 13.8944f + 18.4222f^2 - 10.2599f^3\right) \) |
| \( b_4 = \exp\left(1.4681 + 12.258f - 20.7322f^2 + 15.8855f^3\right) \) |

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6. Devolatilization (Homogeneous)

1. \( \text{CH}_4 + \text{O}_2 \rightarrow \text{CO} + \text{H}_2 + \text{H}_2\text{O} + \text{Heat} \)
2. \( \text{CO} + \text{H}_2\text{O} \rightleftharpoons \text{CO}_2 + \text{H}_2 \)
3. \( \text{O}_2 + 2\text{H}_2 \rightleftharpoons 2\text{H}_2\text{O} \)

Rate constants

For coal,

\[
A_v = 0.2 \times 10^{05} (s^{-1})
\]
\[
E_v = 5941 \text{ (J} \text{mol}^{-1} \text{K}^{-1})
\]

For biomass,

\[
A_v = 6.0 \times 10^{13} (s^{-1})
\]
\[
E_v = 250 \text{ (kJ} \text{mol}^{-1})
\]

7. Char combustion (Heterogeneous)

1. \( \text{C}_{\text{char}} + \frac{1}{2} \text{O}_2 \rightarrow \text{CO} + \text{Heat} \)
2. \( \text{C}_{\text{char}} + \text{CO}_2 \rightarrow 2\text{CO} \)
3. \( \text{C}_{\text{char}} + \text{H}_2\text{O} \rightarrow \text{CO} + \text{H}_2 \)

Rate constants

For coal,

\[
A_c = 497 (\text{kg}m^{-2}s^{-1}(\text{Nm}^{-2})^{-1})
\]
\[
E_c = 8540 (\text{J} \text{mol}^{-1} \text{K}^{-1})
\]

For biomass,

\[
A_c = 0.04 (s^{-1})
\]
\[
E_c = 74.8 (\text{kJ} \text{mol}^{-1})
\]

6.4.2. Grid Independency Test

A grid independence test was carried out to reduce the computational time as well as to build up confidence level. For grid independency test, case A1 (Air firing under 80% coal and 20% biomass) was selected. Three different sets of non-uniform grid systems were successfully tested called Set-A, Set-B and Set-C with similar meshing scheme. Comparatively refined meshes were adopted in the burners’ zone and the exit of the furnace compared to the rest of the computational domain. Selected grid statistics were given in Table 6.8. In order to compare the results for the three different grids, temperature distributions, flue gas velocity in flow direction, CO\(_2\) and O\(_2\) mass fraction distribution along the centreline of the furnace zone are considered. In Figure 6.3, a comparison of gas temperatures and gas velocity, CO\(_2\) and O\(_2\) mass fraction distribution are presented for the selected grid systems. It is seen that the percentage error of values of the selected variables for the change of first two set of grid is comparatively higher than the latter two set of grid. Comparatively, grid with finer cell (in set-C) and medium cells (in set-B) cells represents almost similar results compared to the coarser grid in set-A. Based on this analysis, the grid
system having 559,006 cells in set-B was chosen for the rest of the numerical analysis under different operation condition with different co-firing ratios.

**Table 6.8**: Grid sensitivity analysis for 20% biomass sharing under air-firing condition (Case-A1).

<table>
<thead>
<tr>
<th>Cell set</th>
<th>Type</th>
<th>Total no. of cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set-A</td>
<td>Coarse</td>
<td>292897</td>
</tr>
<tr>
<td>Set-B</td>
<td>Medium</td>
<td>559006</td>
</tr>
<tr>
<td>Set-C</td>
<td>Fine</td>
<td>1072000</td>
</tr>
</tbody>
</table>

![Graph](https://via.placeholder.com/150)

(a) Set-A
Set-B
Set-C
(b) Flow velocity, m/s

Flow velocity as a function of distance along the furnace centreline for Sets A, B, and C.

(c) CO₂ mass fraction, kg/kg

CO₂ mass fraction as a function of distance along the furnace centreline for Sets A, B, and C.
Figure 6.3: Grid independency test for different parameters as (a) Temperature (K), (b) velocity (m/s), (c) CO₂ mass fraction (kg/kg) and (d) O₂ mass fraction (kg/kg) distribution along the furnace centre line

6.4.3. Validation of the Study

To validate the present CFD model used for the modelling of co-combustion of Victorian Brown coal and biomass in a 550MWth tangentially fired furnace, a comprehensive study was conducted in a small scale 0.5 MWth combustion test facility considering different co-firing ratios under air firing and oxy-firing cases [59]. As the coal and biomass have different reaction data, modelling of combustion of biomass is a complex process compared to only coal burning. Also, to account for the complexity of the irregular shaped biomass particles along with its devolatilization and char combustion modelling, user defined routines are developed and coupled with the code [59]. In Ref. [59], pulverized coal and highly volatile biomass particle were co-fired through an aerodynamically air staged burner attached with a refractory lined horizontal furnace. From the experimental work of Smart measured radiative heat flux
was compared with the predicted results for different cases and a reasonably
good agreement was observed. The overall variation between the numerical
and experimental results was less than 10% [59]. For a large scale power plant,
it is not only difficult to experiment the biomass co-firing concepts in a
dedicated coal firing furnace, it will also lead to the interruption of regular
generation of power. Also retrofitting a large scale dedicated power plant boiler
is expensive. So, the predicted results are quite impossible to compare with
experimental data from plant, such as measured flow parameters,
temperatures, emissions etc. Hence, there are limitations to validate the
simulation result obtained with co-firing concepts in dedicated large scale coal
firing plant. This issue was addressed by validating the numerical methodology
against a lab scale furnace in author’s previous work [59]. Confidence on this
numerical methodology was further achieved by comparing the trends of the
simulated results for both air-firing and oxy-firing cases with different biomass
sharing co-fired with coal against the brown coal combustion results in the
same furnace as given in the authors previous work in Ref. [100]. The numerical
study given in Ref. [100] is conducted and validated against the plant data for
combustion only. Predicted peak flame temperatures for only coal
(Reference case), 20% biomass (case A1), 40% biomass (Case A2) and 60%
biomass (case A3) sharing cases under air-firing and different oxy-firing cases
are presented in Figure 6.4. The profile observed for different co-firing cases
were compared with the only coal combustion case under the similar
combustion scenario. It is observed that, compared to only coal firing case, co-
firing of biomass having lower calorific value leads to lower peak flame
temperature inside the furnace. With the increase of biomass sharing, the peak
flame temperature is reduced. This observation is in line with the author’s
previous numerical work [59] for co-combustion modelling in small scale
furnace. Similar numerical modelling of L. Álvarez et al. [158], Yin et al. [71]
and Ma et al. [82] supports the outcomes of the present numerical modelling. These studies showed similar result where the contribution of biomass leads to the decreased temperature. Also the experimental work conducted by Molcan et al. [90] considering a number of biomass and coal co-firing ratios, justified the present numerical work that addition of biomass to coal led to lower flame temperatures. Hence, similarity in the predicted trends of flame temperature observed in the present cases compared to the available experimental as well as numerical study of similar type provided a level of confidence. Hence, the present simulation is carried out to investigate the performance of co-firing in a large furnace under different combustion environment especially in the oxy-fuel scenario.

**Figure 6.4:** Effects of peak flame temperatures for different co-firing ratios under different combustion environments.
6.5. Results and Discussion

As mentioned earlier, the present co-combustion concept modelling of coal and biomass is conducted based on the reference case of coal only combustion in a 550 MWth utility boiler. A series of numerical modelling considering three different co-firing ratios and four different combustion environments were investigated as given in Table 6.2. Results were presented in terms of temperature distributions, flow distribution in different plane of the furnace, various species distributions such as $\text{O}_2$, $\text{CO}_2$ distribution in the main reaction area. All these results are presented in the following section of the chapter.

6.5.1. Effects of Temperature Distribution in Different Cases

The flue gas temperature distribution along the height of the furnace at the mid plane for all the cases are presented in Figure 6.5. In all the cases, temperatures in the secondary air flow and in the burner gas flows were set at 473 and 397 K respectively. In general, fuel mixes with the oxidizer in the main and inert burner area leading to higher flame temperature compared to other area inside the furnace. This is due to the reaction of highly volatile matters and the available oxygen. Compared to the main reaction zone, a decrease in the flame temperature is observed in the upper furnace wall. This is due to less enrichment of $\text{O}_2$ and fuel compared to main reaction zone (shown later). The temperature distribution for different biomass co-firing cases under selected combustion cases were presented for hopper region, burner region, water wall and the convective tube bank region including super heater, reheater, economiser etc. in Figure 6.6.

It can be clearly seen that the temperature decreases as the combustion environment is changed from air-firing to oxy-firing by the replacement of $\text{CO}_2$ with $\text{N}_2$ in secondary flow through SAD systems. This can be explained from
the thermodynamic behaviour and properties of N₂ and CO₂. An increase in oxy-fuel (OF) percentage corresponds to a reduction of CO₂ amount. The reduction in the recycled flue gases contributes to the difference in flame emissivity and thus flame temperature. Compared to N₂, specific heat capacity of CO₂ is high. Hence, an increase in O₂ concentration corresponds to a decrease in CO₂ for higher OF cases leading to higher flame temperature. Besides significant contribution of the replacement of N₂ to CO₂, oxygen (O₂) concentration and residence time are the two dominant factors to control the flame temperature inside the furnace in the oxy-firing cases. According to the Chalmers’ approach [343], the reduced volumetric gas flow was applied in the oxy-firing cases which are quite sufficient to stabilize the flame temperatures. The inlet flow conditions of oxidizer gases, in all oxy-fuel cases were reduced in proportion to the volumetric flow rates by fixed ratios with respect to the air firing case.

It is found that with the increase of biomass sharing peak flame temperature is decreased in air-firing case. This can be supported with the lower calorific value of the biomass sharing in the latter cases. Also, this observation is in line with the findings in small scale study [59]. On the other, for different oxy-fuel cases such as Case B, Case C and Case D (Table 6.2), a similar trend is observed with the increase of biomass sharing. This can be explained by the O₂ enrichment environment with the improvement of oxy-fuel conditions (from Case B to Case D) leading to increase the flame temperature. In all the co-firing cases (Case 1-3), slightly higher temperature is found in oxy-firing Case D (29%O₂ and 71%CO₂) compared to respective air-firing case (23% O₂ and 77% N₂). Similar findings have been reported in literature [205]. In this study, the peak flame temperatures for the air firing cases of A1, A2 and A3 are found to be 1887 K, 1837 K and 1769K respectively.
Figure 6.5: Flue gas temperature (K) distributions in the plane along the furnace centreline for different cases considered.
Figure 6.6: Temperature (K) distribution along the centreline of the furnace for different co-firing cases under different combustion cases.
The flue gas temperature (K) distribution in different burners in X-Y plane for different cases at the mid plane of (i) upper main burner (UMB), (ii) intermediate main burner (IMB), (iii) lower main burner (LMB), (iv) upper inert burner (UIB), (v) intermediate inert burner (IIB) and (vi) lower inert burner (LIB) from top to bottom respectively for all the cases considered in this study are presented in Figure 6.7. It is seen from the figure that compared to inert burner, a higher flame temperature is observed in the main burner area for all the cases considered. It is found that the biomass particle burned out earlier in the system. Biomass particles appeared to be combusted at a relatively higher rate in the near burner region and burn in situ because of highly volatile content. In all the cases, biomass particles burn near to the main burner and
inert burner region where the peak flame temperatures are observed for respective cases. With the increase of biomass sharing in case 2 and 3 (including air firing and oxy-firing), possibility of ignition of fuel within the furnace increases. Increase in the sharing of biomass corresponds to the increase in volatile content. Higher volatile content generally produces more off-gases which results larger volume of flames. Higher volatile content in higher sharing of biomass and the higher char reactivity of biomass compared to coal ensures the faster burning of biomass particles within the furnace. Though, higher volume of flames with lower temperatures are found with the increase of biomass sharing in all the cases, but the effects of moisture content and lower calorific value of the biomass fuels reduces the contribution of highly volatile content leading to lower flame temperature in all the cases. For different combustion cases, higher temperature range is found for co-firing case 1 compared to case 2 and 3. The dominant effect of the lower calorific value and moisture content of biomass dampens the effect of volatile content. Therefore the major effect of the lower calorific value of biomass contributes to lower the flame temperature.

6.5.2. Effects of Flow Distributions in Different Cases

Due to variation of flow conditions under different combustion environments and the coal/biomass sharing, it is important to investigate the flow distribution in the main reaction zone of the tangentially fired furnace. With the change of flow conditions in air-firing to oxy-firing cases, combustion characteristics are significantly varied due to change in mixing of fuel with oxidizer. For all oxy-fuel cases, a substantial decrease of the flow velocity is apparent due to the reduction of the mass entering rates in the furnace. With the increase of oxy-fuel conditions, in the Case B, Case C and Case D; amount of total oxidizer gas supplied to the furnace were 114.35 kg/s, 106.09 kg/s and 99.2 kg/s respectively.
Figure 6.8: Mean velocity (m/s) distribution in the vertical plane along the furnace centreline for different cases considered.
This strategy of lowering the flow in higher oxy-fuel environment was applied based on the Chalmer’s approach [343]. The addition of irregular shaped biomass particles plays a vital role in the overall aerodynamics inside the furnace. The arrangement of the burner position and layout shown in Figure 6.2 was chosen to consider the creation of recirculation characteristics in the main reaction zone. This will provide the better mixing characteristics of the fuel with biomass leading to improved combustion performance. As mentioned earlier, ducting system of 3, 4, and 7 were assumed to be out of service for the present investigation in order to compare the outcome of the co-firing concepts with the only coal combustion results documented elsewhere [100].

Figure 6.8 presents the velocity distributions in the vertical plane along the furnace centre line for all the cases considered. It is seen that comparatively lower flow is observed in the hopper region for Case B, C and D compared to Case A. Similar findings have been observed for temperature distributions in the same region of furnace. This assured that flow velocity has direct influence on the combustion process. In the burner zone, the maximum value of the average Z-velocity component for Case A, Case B, Case C and Case D are 18.02, 16.23, 15.08, and 13.01 m/s, respectively as expected. Though, coal biomass ratio is varied for different cases, the total fuel flow rate maintained constant in this study.
Figure 6.9: Oxygen (O\textsubscript{2}) mass fraction (kg/kg) distributions in different burners in X-Y plane for different cases, (from top to bottom, at the mid plane of (i) UIB, (ii) IIB, (iii) LIB, (iv) UMB, (v) IMB and (vi) LMB).
6.5.3. Effects of O\textsubscript{2} Concentrations Distribution in Different Cases

It is important to know the O\textsubscript{2} concentration distribution in the furnace especially in the burner region. The O\textsubscript{2} mass fraction distributions (kg/kg) in the X-Y plane for all the cases considered at the mid plane of (i) upper intermediate inert secondary air duct (UIISAD), (ii) upper inert secondary air duct (UISAD), (iii) lower intermediate inert secondary air duct (LIISAD), (iv) lower inert secondary air duct (LISAD), (v) upper main Secondary air duct (UMSAD1&2), (vi) intermediate main secondary air duct (IMSAD1&2) and (vii) lower main secondary sit duct (LMSAD) from top to bottom respectively are presented in Figure 6.9. According to the data given in Table 6.6, higher O\textsubscript{2} concentrations were used through the secondary air ducts as inlet boundary conditions for Case B, C and D compared to Case A. But, prediction shows that comparatively lower O\textsubscript{2} is observed in all the planes near the burner region. This can be explained on the basis of higher residence time of the fuel particle in the main combustion zone especially in the oxy-fuel cases. This higher residence time did lead to higher consumption of O\textsubscript{2} in Case B, C and D compared to Case A. This obvious consumption of oxygen in the combustion zones, in the middle zone of the furnace, was also observed in the previous simulation studies of Nikolopoulos et al. [16]. With the increase of the highly volatile biomass sharing in Case 2 and 3 compared to Case 1, higher consumption of O\textsubscript{2} is expected because of the higher reaction of volatile matter. O\textsubscript{2} distributions in the vertical plane along the centre of the furnace for all the cases are presented in Figure 6.10. It is found that O\textsubscript{2} concentration varied according to its injection rate through the burner ducts and secondary air ducts. Comparatively lower O\textsubscript{2} is observed in the middle of the furnace where peak flame temperatures are found.
Case-A1  Case-B1  Case-C1  Case-D1
Case-A2  Case-B2  Case-C2  Case-D2
Case-A3  Case-B3  Case-C3  Case-D3

Figure 6.10: Oxygen (O₂) mass fraction (kg/kg) distribution in the vertical plane along the furnace centreline for different cases considered.
6.5.4. Effects of CO₂ Concentrations Distribution in Different Cases

The CO₂ mass fraction distributions (kg/kg) in the X-Y plane for all the cases considered at the mid plane of (i) upper intermediate inert secondary air duct (UIISAD), (ii) upper inert secondary air duct (UISAD), (iii) lower intermediate inert secondary air duct (LIISAD), (iv) lower inert secondary air duct (LISAD), (v) upper main Secondary air duct (UMSAD1&2), (vi) intermediate main secondary air duct (IMSAD1&2) and (vii) lower main secondary air duct (LMSAD) from top to bottom respectively are presented in Figure 6.11. According to Chalmer’s approach, with the increase of oxy-fuel scenario, inlet CO₂ was reduced. The variations of CO₂ concentration for different oxy-fuel cases (Case B, C and D) were not significant. But a significant change can be
observed while comparing with Case A (Air-firing case). Around five times higher CO₂ is predicted in all oxy-fuel cases compared to air case. Similar changes were found elsewhere.

Figure 6.12 shows the CO₂ mass fraction (kg/kg) along the vertical plane of the tangentially fired furnace for all the cases examined. No significant changes were found in the furnace main zone except the variation of air to oxy-firing cases. For all the cases, the maximum CO₂ concentrations are found in the furnace reaction zones. This declaration is in line of with the ignition of flame temperature in the reaction zone. Due to higher percentage of volatile matter in biomass, O₂ is consumed quickly in according to homogeneous reactions shown in Table 6.7. As soon as the devolatilization is completed, highly reactive biomass char participated in the oxidation process with the surrounding O₂ leading to the formation of CO₂. This phenomenon is explained in more details by Li [293]. Comparatively, higher CO₂ concentration is predicted for Case B compared to Case C and D, while lowest value is found for Case A as expected due to air firing. Lowest CO₂ values predicted in the flame region were accompanied by the highest CO values for all the co-firing cases (not shown here). According to Boudouard reaction, higher CO₂ concentration has a strong influence on the char oxidation leading to an increase in the CO concentrations in the reaction zone of the furnace.
Figure 6.12: Carbon dioxide (CO$_2$) concentration (kg/kg) distribution in the vertical plane along the furnace centreline for different cases considered.
Table 6.9: Predicted CFD results of all the cases considered at the final exit.

<table>
<thead>
<tr>
<th>Combustion cases</th>
<th>Co-firing cases</th>
<th>Mean temp. (K)</th>
<th>CIA (%)</th>
<th>CO₂ (wt %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air firing</td>
<td>Only coal [80]</td>
<td>635.35</td>
<td>2.05</td>
<td>18.84</td>
</tr>
<tr>
<td></td>
<td>A1</td>
<td>620.10</td>
<td>3.60</td>
<td>15.50</td>
</tr>
<tr>
<td></td>
<td>A2</td>
<td>589.62</td>
<td>5.50</td>
<td>14.15</td>
</tr>
<tr>
<td></td>
<td>A3</td>
<td>561.50</td>
<td>7.20</td>
<td>13.30</td>
</tr>
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<td>9.74</td>
<td>85.76</td>
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<tr>
<td></td>
<td>B1</td>
<td>605.37</td>
<td>13.2</td>
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</tr>
<tr>
<td></td>
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<td>575.90</td>
<td>17.5</td>
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</tr>
<tr>
<td></td>
<td>B3</td>
<td>545.15</td>
<td>21.8</td>
<td>83.30</td>
</tr>
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<td>Only coal [80]</td>
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<td>7.04</td>
<td>85.01</td>
</tr>
<tr>
<td></td>
<td>C1</td>
<td>610.35</td>
<td>11.2</td>
<td>84.21</td>
</tr>
<tr>
<td></td>
<td>C2</td>
<td>581.75</td>
<td>15.5</td>
<td>83.80</td>
</tr>
<tr>
<td></td>
<td>C3</td>
<td>548.65</td>
<td>19.1</td>
<td>83.15</td>
</tr>
<tr>
<td>Oxy-fuel (OF29)</td>
<td>Only coal [80]</td>
<td>631.40</td>
<td>5.49</td>
<td>84.18</td>
</tr>
<tr>
<td></td>
<td>D1</td>
<td>614.35</td>
<td>8.90</td>
<td>83.90</td>
</tr>
<tr>
<td></td>
<td>D2</td>
<td>584.10</td>
<td>12.1</td>
<td>83.25</td>
</tr>
<tr>
<td></td>
<td>D3</td>
<td>553.85</td>
<td>14.8</td>
<td>83.00</td>
</tr>
</tbody>
</table>

6.5.5. Mean Temperature, Carbon in Ash and CO₂ at Exit

Table 6.9 presents the predicted CFD results including mean temperatures, unburned carbon in ash (CIA) and carbon dioxide mass fractions for all the cases considered at the final exit of the furnace. Selected parameters were predicted for different co-firing ratios under different combustion environment and compared with the reference only coal combustion case as given in Ref. [100]. With the increase of biomass sharing for each combustion cases, temperatures were decreased in air-firing case. This can be explained by the less moisture content of coal and lower calorific value of the biomass. While comparing with the air to oxy-firing cases, it is seen that the temperatures slightly increased with the increase of O₂ in each co-firing cases.
Figure 6.13: Radiative heat flux distribution for different cases considered.
It is important to measure the unburned carbon in ash (CIA) for providing guidance to the utility power companies to take cost effective measures by reducing the unburned carbon in fly ash (CIA). Also, the determination of CIA is an essential tool for measuring the efficiency of the power plant. Predicted CIA data were presented in Table 6.9 comparing different co-firing cases under selected combustion scenarios. The data predicted in this study is qualitative. With the increase of biomass sharing, a significant increase of unburned carbon in fly ash was predicted. The high amount of unburned carbon due to sharing of biomass is partially attributed to the large size of the biomass particles. Comparatively, improved burnout was observed with the increase of $O_2$ concentrations in oxy-fuel combustion cases. This can be attributed to longer residence times for the biomass and coal particles and higher oxygen concentration in the furnace. It was found that maximum size of particles (3.00 mm) used in the present study contributed to the unburned carbon from biomass. The increase in unburned carbon in ash with the increase of biomass sharing would reduce boiler efficiency. The $CO_2$ concentrations at the final exit of the furnace are same as to that of presented in Figures 6.11 & 6.12.

6.5.6. Effect of Radiative Heat Fluxes for Different Co-firing Cases

Radiative heat fluxes on the furnace wall for all the cases considered in this study are displayed in Figure 6.13. For the wall boundary condition, similar types of heat input are considered for the burner wall, combustion chamber and the convection and radiation heat transfer of the furnace wall. Figure presented the predicted wall incident heat flux on the radiation region of the furnace wall for all cases investigated. The total net radiative heat flux gradually increased for the oxy-fuel cases. This is due to improved $O_2$ concentrations and the decrease in the volumetric flow rates assumed in the oxy-fuel firing cases. Also with the increase of biomass sharing, radiative heat flux is significantly
decreased. This can be explained similar to the case of flame temperature variations.

With the increase of biomass sharing in case 2 and case 3 (both air firing and oxy-firing), possibility of ignition of fuel within the furnace increases. Increase in the sharing of biomass corresponds to the increase in volatile content. Higher volatile contents generally produces more off-gases which results larger volume of flames. Higher volatile content in higher sharing of biomass and the higher char reactivity of biomass compared to coal ensures the faster burning of biomass particle within the furnace. Though, higher volume of flames with lower temperatures is found with the increase of biomass sharing in all the cases leading to lower radiative heat flux. For different combustion cases, higher temperature range is found for co-firing case 1 compared to case 2 and 3. The dominant effect of the lower calorific value and moisture content of biomass dampens the effect of volatile content. Therefore the major effect of the lower calorific value of biomass contributes to lower radiative heat flux.

6.6. Summary

The main objective of the work was to scrutinize the performance of co-firing concept of pulverized coal and irregular shaped biomass particles (woody type) in a 550 MWth tangentially fired furnace. For this purpose, a series of investigations were carried out combining three different biomass sharing (20%, 40% and 60%) cases under four different combustion environments (air firing, OF 25, OF 27 and OF 29). Different oxy-fuel cases were evaluated based on Chalmers’ approach. Compared to the pure coal combustion, a significant decrease in the flame temperatures with the increase of biomass particle flow was predicted. Relationship between the air-firing to oxy-firing cases was
presented on the basis of peak flame temperature for retrofitting purpose. It was found that the increase of biomass sharing was responsible for increasing the flame volume while the peak flame temperature decreases. Comparatively improved burnout was observed in oxy-firing cases. The amount of unburned carbon in ash was predicted to increase when co-firing ratio increase due to the large size of the biomass particles.
CHAPTER 7. Development of Three Dimensional Slag Flow Modelling in an Industrial Furnace

Overview: In this chapter, the development of three dimensional slagging combustion models for coal-firing in an industrial furnace under oxy-fuel combustion condition is presented. In order to describe the slagging combustion, a Eulerian-Lagrangian model of the gas-particle flow was coupled with the particle-wall interaction sub-model. This study was performed considering two stages. Validation of the model was achieved by comparing the available experimental and numerical slag thickness data for coal-water slurry combustion in 3MWth small scale furnace. The slag thickness deposited on the furnace wall was found to be reasonably in good agreement with the available data. Visualization of the transient slag deposition and flow characteristics under air and oxy-firing cases were presented. The deposited slag thicknesses for both the cases were found in the range of 0-1.0 mm. The average molten slag velocity was 0.0001 m/s due to higher viscosity and surface tension properties. Slightly higher amount of slag was deposited in oxy-firing cases due to slower char oxidation rate. Species distributions (O₂, CO₂, H₂O, CO), gas temperature and flow dynamics were critically compared in both cases. Later, validated slag model was applied in a 550MWth coal-fired furnace for determining the effects of slagging behaviour of the Brown coal combustion under oxy-fuel condition. Results are presented in terms of slag thickness, slag velocity on different walls under oxy-fuel condition. The effects of species mass fraction, flame temperature and flow distribution in different plane of the furnace were presented.
7.1. Introduction

Slagging is a process of combustion in which ash/char particles are heated at a temperature above the fusion temperature, and then becomes molten and thus deposited along the furnace refractory wall. These molten particles form a layer of film called slag [53]. Formation of slag is accountable for the decrease in the disposing of unused mineral content in the environment, reduced energy efficiency, broader fuel flexibility and higher percentage of low-carbon content slag residues for applications [57, 58]. Also, the deposited layer of film works as a coating for the prevention of heat loss in the gasifiers. But, it reduces the overall efficiency of the plant. In order to allow slagging combustion, it is important to sustain an optimum state which requires comprehensive information about the related process and mechanisms.

For designing and optimization of slagging in furnace, it is important to investigate the related process such as particle deposition, slag flow and burning on the wall occurring inside the furnace. In last decade, research attention has been given into the carbon capturing and storage (CCS) systems especially on oxy-fuel combustion using various types of fuels by computational technique. Compared to other systems [16, 106], there have been limited attempts are initiated to investigate the slagging issues. For most of the furnace, it is important to know the effects of interaction between the wall and particles impingement/entrainment. The amount and location of the deposited particles as well as its dynamics is also important. It is quite challenging to identify the problems on-site unobtrusively and with reasonable effort. Hence, CFD modelling is an important solution for slagging issue. A comprehensive review on slagging modelling issues and related process are documented in [55].
An experimental study conducted by Li [243, 251] determined the physical phenomena associated with char–slag transition in an entrained-flow reactor. The physical properties of the char and slag particles were characterized, including the particle density, size, internal surface area and morphology. The major phenomena which indicate the char–slag transition are, density increase, size reduction and surface area decrease. Predicted results showed that the particle capture efficiency was a function of coal conversion. In recent years, a number of computational attempts [28, 39, 240, 242, 243, 249, 251, 256, 344] have been performed to investigate the ash formation and transport process in pulverized fuel combustion system, to avoid these experimental problems.

Modelling in a slagging type combustor has shown limited progress in the literature compared to other conventional combustion processes [55]. Hence, the main goal of the present study is to develop a comprehensive 3D slag flow model in an industrial furnace using CFD. Also, to examine the factors associated with the deposition characteristics that experience between combustion and slagging- called slag wall interactions. In this study, a 550MWth tangentially-fired furnace under oxy-firing condition is considered to identify the slagging behaviour and related issues. For validation purpose, a 3MWth coal slurry combustor was used where slag thickness and surface flow were predicted. Also, this study looks at the effects of different species level and thermal and flow behaviour under air and oxy-fuel conditions using a commercial CFD code coupled with some user-defined subroutines.

7.2. Progress in Slag Modelling

In last two decades, many numerical efforts have been demonstrated for the development of slagging model. The following section briefly describes the progress in the development of different slagging models.
**1D model:** Seggiani [242] developed a simplified model for the simulation of time varying slag flow in an entrained flow reactor. In modelling the slag formation, different physical properties such as critical viscosity, specific heat, thermal conductivity were taken into account. This 1D slag model of Seggiani [242] considered Reid and Cohen assumptions [252] and integrated with a 3D code to obtain mass deposition rate, gas temperature and heat flux. Temperature of critical viscosity is considered as an important parameter which is dependent on the composition of slag. Later, Wang [245, 246] conducted another steady state model to determine the deposition and burning characteristics during firing of coal and wood. In this model, Particle impingement and particle sticking characteristics are applied by using Wood’s [253] and Walsh’s [254] mechanisms. The specialty of this model is the wall burning and slag flow process, but only limited for molten slag modelling. Compared to Seggiani’s model [242], this Wang model reflects the wall burning phenomenon when fuel particles are stuck on the slag surface and its consequence on char oxidation and heat transfer performance. But both of the model cannot determine the slag behaviour in others direction.

**2D model:** Yong [237, 238] developed a steady state model to describe the flow and heat transfer characteristics in slag layer of solid fuel gasification by combining the model developed by Seggaini [242] and Wang [245, 246] as described earlier. In this modelling, an updated temperature profile is assumed replacing Seggaini’s assumptions [242]. Bockelie [255] and Chen [239] extended the 1D slag model into the 2D wall surface in fuel combustor. But slag flow is considered in one direction only. This 2D method considers the spatial distribution of ash particle deposition. This approach cannot completely solve the 3D flow behaviour. Liu and Hao [256] modelled a two dimensional slag flow in an entrained flow gasifier using the volume-of-fluid (VOF) model. Ni
[240] used the same technique to model the multiphase multilayer slag flow and phase transformation considering two-dimensional mesh with uniform ash deposition rate.

3D model: Most of the slagging studies are based on 1D and 2D modelling. Only few studies attempted to 3D model. Chen [56] developed a comprehensive slag flow model to determine the slag behaviour during coal combustion and gasification in a 5MW pressurized combustor. This model integrated different models for fluid and particle trajectories modelling implemented in a commercial CFD code. This model completely decides the 3D features of char/ash deposition, slag flow, as well as heat transfer through the slag layer. The result showed that 1–2 mm slag layer is formed on the refractory wall which is basically molten. The mean slag flow rate is normally about 0.1 mm/s. The relationship between the slag thickness and slag velocity, heat flux and slag temperature are presented in the numerical work of [245]. It is observed that slag velocity decreases with the increase of slag thickness. Similar trend is observed in the study of Chen [56].
Figure 7.1: Structure of the slagging model combining gas-particle combustion phase and particle-wall interaction phase model.

7.3. Model Development of Slagging Combustion

7.3.1. Fundamental Modelling Concept

An understanding and fundamental knowledge in modelling of slagging is important for predicting the particles deposition, conversion into slag thickness and related heat transfer. In general, the modelling of slagging consists of several complexes and simultaneous processes such as the slag flow, particle capture and particle consumption modelling. After the gas-particle phase, some of the fuel particle hits the wall of the furnace, some of the particles are captured and some of the particles are rebound from the wall based on the capturing criteria in wall-particles interaction phase. In modelling of slagging, gas and slag flow are treated as separate single phases. So this is not a complete two-phase model but rather two single phase models attached at the slag
surface. The coupling of the two phases is achieved by a modified set of boundary conditions based on semi-empirical relations. It is assumed that the slag thickness is very small in relation to the particle size of the gas flow which is one of the main limitations of slag modelling. Therefore, no adaptation of the volume grid to the slag surface is necessary. The detailed structure of the slagging model by combining solid-gas phase and particle-wall interaction is presented in Figure 7.1.

7.3.2. Gas–particulate Phase Modelling

In slagging modelling, three dimensional CFD simulation of solid fuel combustion is carried out by a commercial CFD code, AVL Fire version.2009.2 coupled with user-defined sub-routine. To demonstrate the applications of combustion modelling in CFD, a detailed description of the used model is given in [1]. Eulerian/Lagrangian approach is considered for the modelling of fluid/particle phase modelling. The energy balance equation for radiative and convective heat transfer is used for tracking the particles temperature is given in the following equation:

\[ m_p c_{p,p} \frac{dT_p}{dt} = \pi d_p^2 \left( h(T_g - T_p) + \epsilon_p \sigma(T_w^4 - T_p^4) \right) \]  

Equation (7. 1)

In this study, the Eddy Breakup (EBU) model, a typical mixed-is-burnt combustion model is applied for all the combustion modelling cases. This model determines whether O\(_2\)/fuel is in limiting condition or not. The detail of this turbulence controlled combustion model is given in Ref. [60]. This can be expressed by the following equation:

\[ \rho \bar{\dot{r}}_{fu} = \frac{c_{fu}}{T_R} \rho \min \left( \bar{y}_{fu}, \frac{y_{ox}}{S}, \frac{c_{pr} \bar{y}_{pr}}{1+S} \right) \]  

Equation (7. 2)

In order to solve the chemical reactions such as devolatilization and char burnout, appropriate subroutines were written and coupled with the code. As combustion consists of complex carbon-oxygen reactions, devolatilization and
char oxidation are expressed in the form of homogeneous and heterogeneous reactions. In Ref. [95], a three steps chemical reactions were suggested for the process of devolatilization and char oxidation. As char oxidation is mainly governed by the diffusion of $O_2$, global reaction is considered as suggested by [95-97]. Appropriate rate constant for the process of devolatilization and char oxidation were used given in Table 7.1.

For turbulence, a k-$\varepsilon$ model is considered in the present study. For pressure velocity coupling, the SIMPLE algorithm is used. A general convergence criterion of absolute residual value set to $10^{-4}$ for all the variables considered. In order to achieve the level of confidence, grid with $4.65\times10^5$ cells is considered with minimum computational time with reasonable accuracy in the present study.

<table>
<thead>
<tr>
<th>Processes</th>
<th>$A_c$</th>
<th>$E_c$</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Devolatilization</td>
<td>$0.2\times10^5$ (s$^{-1}$)</td>
<td>$4.64\times10^7$ J/kmol</td>
<td>[96, 268]</td>
</tr>
<tr>
<td>Char oxidation</td>
<td>$300$ kg/ (m$^2$sPa)</td>
<td>$162$ kJ/mol</td>
<td>[259, 345]</td>
</tr>
</tbody>
</table>

### 7.3.3. Slag Flow Model

In modelling of slag deposition characteristics, the significant assumptions considered as lower slag thickness, unidirectional flow, shear stress due to captured particles and slag properties are used at slag mean temperature. For the slag flow, Chen [56, 239] describes the three dimensional modelling that includes discrete phase and volume of fluid model for the modelling of slag layer in horizontal and vertical furnace. The slag film flow model works based on Eulerian-Lagrangian approach which can be described by the mass, momentum and energy conservation equation. The basic governing equation for slag filming flow is the slag thickness equation. It is a slightly modified
formulation of the continuity equation, which is transformed to conservation of slag film thickness as follows:

\[
\frac{\partial \delta}{\partial t} + \frac{\partial \delta u_1}{\partial x_1} + \frac{\partial \delta u_2}{\partial x_2} = \frac{1}{\rho A_s} (S_{mD} - S_{mV})
\]  

Equation (7.3)

One of the important features of the modelling of slag filming is the use of analytical slag velocity profiles instead of a momentum equation. All forces acting on the slag layer resulting in shear forces which the slag film applies to the furnace refractory wall. There is a direct relation between the distribution of shear forces across the slag layer formed and the velocity profile of the film surface flow. By applying the Boussinesq hypothesis for turbulent eddy viscosity \( \varepsilon_m \), the velocity profile of slag due to applied shear forces \( \tau \) can be written as:

\[
\tau = (\partial + \varepsilon_m) \frac{\partial u}{\partial y}
\]  

Equation (7.4)

The distribution of shear force across the slag due to interfacial shear \( \tau_I \), gravity and longitudinal pressure gradient is given by:

\[
\tau(y) = \left( \rho g - \frac{dp}{dx} \right) (\delta - y) + \tau_I
\]  

Equation (7.5)

By applying the usual definitions for dimensionless distance from the wall

\[
y^+ = \frac{y u_t}{\delta}
\]  

Equation (7.6)

The dimensionless flow velocity \( u^+ \) and friction velocity \( u_t \) are as follows:

\[
u^+ = \frac{u}{u_t}
\]  

Equation (7.7)

\[
u_t = \sqrt{\frac{\tau_w}{\rho}}
\]  

Equation (7.8)

Equation (7.5) can be cast into the following expression for the dimensionless velocity profile:
\[
\frac{\partial u^+}{\partial y^+} = \frac{\tau_{w} u^*}{1 + \varepsilon_m} \tag{7.9}
\]

The wall shear force \((\tau_w)\) is the shear force \((\tau)\) at \(y=0\). For laminar flow, turbulent eddy viscosity \((\varepsilon_m)\) equals to zero. In the case of horizontal flow, driven only by interfacial shear force \((\tau = \tau_w = \tau_I)\), the profile results to

\[u(y) = \frac{\tau_I}{\mu} y \tag{7.10}\]

If there is no shear force, but gravity and pressure gradient only, the profiles result to

\[u(y) = \frac{1}{\mu} (\rho g - \frac{dp}{dx}) (\delta y - \frac{y^2}{2}) \tag{7.11}\]

If the wall is not vertical, only the body force component parallel to the wall is used. For the case of laminar flow, the profiles of above two equations can simply be added to yield the general velocity profile [346, 347]. The mean slag velocity can be obtained by integrating over the slag thickness \((\delta)\) as follows:

\[\bar{u}_L = \frac{\delta}{6\mu} [2\delta (\rho g - \frac{dp}{dx}) + 3\tau_I] \tag{7.12}\]

For the turbulent flow, in equation (7.5), it is important to define the eddy viscosity \((\varepsilon_m)\). The eddy viscosity or turbulent viscosity can be defined as a function of wall distance \(y\). After integrating equation (7.5), the average turbulent film velocity can be expressed as follows:

\[\bar{u}_L = \frac{4g}{594} \left(\frac{\delta}{\delta}\right)^{4/7} \frac{[7\delta (\rho g - \frac{dp}{dx}) + 9\tau_I]}{\rho^{11/14} (\rho g \delta - \frac{dp}{dx} \delta)^{3/14}} \tag{7.13}\]

### 7.3.4. Char Capture Model

After particle introduction in the furnace, the char/ash particles hit the furnace wall, possible four major processes such as rebounding, splashing, deposition and thermal breakup can be occurred based on the thermal and hydraulic properties of the particles controlled by the capturing conditions. In most of the
combustion cases, some of these heated particles are captured on the wall and some particles are rebound from the wall. Hence, determination of the amount of capturing criteria is important in modelling the slag formation behaviour in CFD. Several authors developed the particle capture sub-model to set-up particle capturing criteria for the formation of slag film on the refractory wall. Recently, Chen [56, 239] used the particle capture criterion considering three major parameters, temperature of the particle (Tp), temperature of the combustor wall (Tw), and the carbon conversion of the particle (C). Based on the assumptions given in Refs. [241, 243], when both the walls and the particles are sticky, the ash/char particle will be captured. If any one of the wall is not sticky, there is still a possibility for particle trapping. This trapping is determined by the Webber number having a critical value of 1.0 [244].

In the present study, the model of Kuhnke [348] is considered for settling this particle capturing behaviour. The model of Kuhnke [348] is an advanced wall interaction model where wall temperature (T_w), temperature of particles (T_p), particle size and its dynamics are important. The particles properties such as viscosity, density, thermal conductivity, specific heat, surface tension etc. are important. This model is useful to investigate the spray/wall interaction in spray-type applications where wall temperature and the particle velocity are of importance. This model considers the mass of particles, which is deposited at the wall as well as the size and its dynamics after the impingement or entrainment. According to the model, the slag formation strongly depends on the wall and heated particles temperature. In this model, the impact of dimensionless wall temperature (T*) besides the impact of dimensionless velocity (V*) is considered as the capturing criteria. The definition of dimensionless wall temperature and dimensionless particles velocity are as follows respectively.

\[
T^* = \frac{T_w}{T_s}
\]  

Equation (7.14)
\[ V^* = \frac{(\rho_d d_d \mu_d T)}{\sigma_d \mu_d T^3} \]  

Equation (7.15)

The graphical capturing criterion is presented in Figure 7.2 highlighting all the cases. From the figure, four important conditions are as follows:

![Diagram showing particle capturing model used for slagging combustion][1]

**Figure 7.2:** Particle capturing model used for slagging combustion [348].

a. Deposition: If the value of dimensionless wall temperature, \( T^* \) is less than 1.1 and particles velocity is low, then the impacting particles are fully deposited on the wall and create a layer of slag.

b. Splashing: If the value of dimensionless wall temperature \( T^* \) is less than 1.1 but the velocity of the impacting particles are higher, the particles are divided and smaller particles are formed after the impingement. Here, a small amount of particles mass are transformed to the slag mass.

c. Rebound: If the dimensionless wall temperature, \( T^* \) is greater than 1.1 and a low particle velocity is observed, a sheet layer between particles and the wall is

[1]: https://example.com/diagram
formed which prevents a direct contact of the particles and the wall. Here, no wall slag deposited.

d. Thermal breakup: If the dimensionless wall temperature, \( T^* \) is greater than 1.1 and a higher particles velocity, the particles disintegrated into secondary particles and no wall slag if deposited.

### 7.3.5. Wall Burning Sub-model

After the deposition of char/ash particles on the furnace wall and formation of thin slag layer, a slow wall burning process may occur if the required oxygen level is available. The wall burning process is dependent on the deposition level of char particles. A detailed analysis about the wall burning process are given in Refs. [245, 246]. Basically, wall burning is a slower char combustion process because of the slower diffusion of oxygen (\( O_2 \)) on the external surface of the deposited particles [56, 237-239]. Similar to the char combustion in particulate phase modelling, deposited slag can be combusted using global power-law [27]. This is treated as suitable model compared to any other models [97]. When the char/ash particles are deposited as slag, this slag film may react with the surrounding gases steadily [269]. But the rate of deposited slag burning will be significantly lower than the particles oxidation due to slower diffusion of \( O_2 \).

### 7.3.6. Wall-film Entrainment Model

At high fluid velocity, the shear force at the slag film surface tears droplets back into the fluid flow. These droplets are generated at or near surface waves. This phenomenon is simulated within the wall-film model and described under the terms of the entrainment model. The entrainment model consists of two parts – first an entrainment mass flux is evaluated, then droplets are generated from this mass flux. The entrainment rate depends primarily on interfacial shear force, deposited film viscosity and surface tension. Droplets which become
airborne are calculated by the gas-particle model. In this study, Schadel-Hanratty Model [349] was considered for entrainment modelling. The critical Weber number, specifying the onset of entrainment is defined as:

$$We_{cr,SH} = \frac{\rho_g u_{rel}^2 \delta}{\sigma}$$  \hspace{1cm} \text{Equation (7.16)}

The relative velocity $u_{rel}$ is:

$$u_{rel} = |\bar{u}_{gas} - \bar{u}_f|$$  \hspace{1cm} \text{Equation (7.17)}

Since the actual mean velocity of the gas phase is difficult to evaluate, the velocity component parallel to the wall of the cell layer from the wall was used. This is a reasonable approach for turbulent flows. When the first droplets start to entrain, the model just computes an entrainment mass flux. This entrainment rate is the amount of mass sheared off the film per unit area and unit time. This rate of atomization is described by an empirical correlation, fits to data of Schadel and Hanratty [349] which gave the model its name:

$$R_{ASH} = X_{RA} u_f \sqrt{\frac{\rho_g \rho_f}{\rho_f}} \cdot 10^{-3}$$  \hspace{1cm} \text{Equation (7.18)}

Where

$$X_{RA} = 0.4 \ln \left(150 \cdot I_R \cdot We_{SH} + 1.4 \cdot I_R \cdot We_{SH}\right)$$  \hspace{1cm} \text{Equation (7.19)}

With the roll wave intermittence factor as a function of excess film flow rate $\Gamma_E$:

$$I_R = 0.15 + 0.75 \Gamma_E, I_R \leq 0.5$$  \hspace{1cm} \text{Equation (7.20)}

### 7.3.7. Slag Properties

Selection of appropriate slag properties is important for modelling of slag formation behaviour. Determination of slag properties such as viscosity, density, specific heat, surface tension and thermal conductivity are dependent on constituents of the fuel particles which can be measured by using X-ray fluorescence (XRF) method [238]. The chemical compositions of the slag vary due to variation of coal slag origination. The temperature of critical viscosity is
one of the most important properties which can be defined as the temperature where a transition between the liquid and the plastic flow is occurred. It is challenging to predict due to abrupt changes between the liquid and solid slag layers interface. Due to lack of data from the experimental studies on the ash properties, sometimes properties are predicted based on correlations [350-354].

The slag properties data used in the present study is given in Table 7.2. A user-defined subroutine was coupled with the CFD code for incorporating the slag properties such as temperature of critical viscosity, dynamic viscosity, density, surface tension, specific heat capacity, latent heat of evaporation, slag emissivity and thermal diffusivity.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Values</th>
<th>Unit</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature of critical viscosity</td>
<td>1680</td>
<td>K</td>
<td>[242]</td>
</tr>
<tr>
<td>Dynamic viscosity</td>
<td>1–20</td>
<td>Pa.s</td>
<td>[355]</td>
</tr>
<tr>
<td>Density</td>
<td>2780</td>
<td>kg/m³</td>
<td>[247, 354]</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>1.73–1.80</td>
<td>W/m.K</td>
<td>[247, 354]</td>
</tr>
<tr>
<td>Surface tension</td>
<td>430 x 10⁻³</td>
<td>N/m</td>
<td>[247, 354]</td>
</tr>
<tr>
<td>Specific heat cp</td>
<td>1.3825</td>
<td>kJ/kg.K</td>
<td>[247, 354]</td>
</tr>
<tr>
<td>latent heat</td>
<td>355 x 10³</td>
<td>J/kg</td>
<td>[356]</td>
</tr>
<tr>
<td>Slag emissivity</td>
<td>0.83</td>
<td></td>
<td>[247, 354]</td>
</tr>
<tr>
<td>Thermal diffusivity</td>
<td>4.5 x 10⁻⁷</td>
<td>m²/s</td>
<td>[242]</td>
</tr>
</tbody>
</table>
7.4. **Validation of the Model in Lab-scale Combustor**

7.4.1. **Physical Model Used**

For the validation purpose, the physical model of 5MWth coal water slurry scaled combustor given in Refs. [285, 357] was considered in the present study. The schematic diagram of the computational domain showing important components is presented in Figure 7.3. It is seen that a burner is mounted at the center of the front end of the combustor for facilitating the coal/oxidizer flow into the reaction zone. As the fuel is mixed with water, an atomizer is attached with the burner design. A simplified design of the furnace is given in Figure 7.4. The position of the atomizer is at a small distance down from the burner center. The oxidant flow consist of recycled flue gas such as O\(_2\), N\(_2\), CO\(_2\), H\(_2\)O are stabilized by a constant swirling flow to the furnace. The fuel properties used for this study were given in Table 7.3. For coal, the particles mean diameter of 200 \(\mu m\) was used for both air-firing and oxy-fuel cases.

7.4.2. **Fuel Properties, Cases and Boundary Values**

The different operating conditions were characterized by air-firing and oxy-firing cases. The compositions of O\(_2\), N\(_2\), CO\(_2\) and H\(_2\)O for both the cases are presented in Table 7.4. The operating conditions used in this study were based on the optimized and scaled down to a 3 MWth operating condition in Ref [357]. For all cases, a constant temperature and high pressure were maintained for oxidizer and atomizer flows. The coal-water slurry mass flow rate was maintained at 0.1 (kg/s) for all the cases simulated. For stability and better mixing of the flow, a constant swirl number of 0.8 was used. For different section of the furnace wall, no-slip boundary conditions were assumed and constant wall temperature and emissivity were used for the furnace. At the flue
gas and molten ash exit of the furnace, zero gradient for all the variables were assumed.

**Figure 7.3:** Schematic diagram of the Physical model used for slagging combustion.

**Figure 7.4:** A simplified design of the burner used for slagging modelling.
Table 7.3: Fuel properties and particle data used for the modelling.

<table>
<thead>
<tr>
<th>Proximate analysis (wt%, ar)</th>
<th>Ultimate analysis (wt%, ar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture content</td>
<td>6.40</td>
</tr>
<tr>
<td>Ash content</td>
<td>7.00</td>
</tr>
<tr>
<td>Volatile matter</td>
<td>33.1</td>
</tr>
<tr>
<td>Fixed carbon</td>
<td>53.5</td>
</tr>
<tr>
<td>HHV, MJ/kg</td>
<td>29.15</td>
</tr>
</tbody>
</table>

Table 7.4: Boundary parameters for different coal-water slurry combustion cases.

<table>
<thead>
<tr>
<th>Cases</th>
<th>Flow conditions</th>
<th>Oxidizer compositions</th>
<th>Coal supply</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Q (kg/s)</td>
<td>T (K)</td>
<td>P (bar)</td>
</tr>
<tr>
<td>Air</td>
<td>1.12</td>
<td>305</td>
<td>4.0</td>
</tr>
<tr>
<td>Oxy</td>
<td>1.13</td>
<td>305</td>
<td>4.0</td>
</tr>
</tbody>
</table>

7.4.3. Comparison of Slag Thickness for Validation

It is seen from the literature that a significant amount of published plant data for the combustion of various types of solid fuels was available for the combustion models used in CFD. Available combustion models in CFD are quite generic models and applicable to a wide range of combustion problems. But little information is available for the slag formation phenomenon. Hence, the validation of the developed slagging model is carried out against the visualization of the CFD data of slag formation predicted in Chen’s model [56]. Figure 7.5 shows the comparison of deposited slag thickness between the Chen model [56] and the present model under oxy-firing condition. The validation is qualitative in nature and gives an overall understanding of the qualitative accuracy of the developed model. Though the presence of some discrepancies in the modelling was observed while validating against the CFD data, but overall
a reasonable data range was predicted. It is seen that the deposited slag layer spread over the bottom wall of the furnace due to flows of the side wall and also gravity. The deposited slag thickness over the wall was found in the range of 0-1 mm. This is mainly due to the transient build-up of ash/char particle deposition. Similar findings have been observed in the study of Chen [56]. Thus, the CFD faithfully reproduced the slag deposition characteristics for the selected combustion case.

Figure 7.5: Comparison of slag thickness between the (a). Chen’s model [56] and (b). Present model.

Figure 7.6: Velocity (m/s) and gas temperature (K) distribution for (a) air-firing, (b). oxy-firing case.
7.4.4. Effect of Temperature and Flow Distributions

In this study, a comprehensive investigation on the thermal and slagging characteristics of coal-water slurry combustion has been investigated considering air and oxy-fuel combustion environment. Results are presented based on flow dynamics, temperature distribution and species distributions etc. Figure 7.6 presents the flow distribution of the oxidizer and gas temperature distributions for both the cases. The velocity distribution along the reactor length is presented and no significant variation is observed as can be seen from the flow condition given in Table 7.4. This is due to similar swirling flow (swirl number =0.8) considered for both the cases. Comparatively lower recirculation is visualized in oxy-firing case which is responsible for lower residence time leading to lower mixing of the fuel with oxidizer. This lower residence time lead to lower flame temperature in oxy-firing case. The visualization of temperature shows that peak value is found too far from the burner exit in both cases. This is due to injection of coal-water slurry particles near the burner and reaction area. The fuel/oxidizer components having higher fraction of H₂O in slurry compositions compared to coal/air flow lead to delayed ignition in the oxy-firing case. The peak temperature for air and oxy-firing cases were found 2085 and 1905 K respectively.

7.4.5. Effect of Species Distribution Under Air and Oxy-fuel Condition

Figure 7.7 presents the distribution of the oxidizer (O₂) and associated CO₂ concentration contours for air-firing and oxy-firing cases. These two parameters are closely related to each other. Prediction of mass fraction (kg/kg) distribution of CO₂ and O₂ are important phenomena in oxy-fuel cases which contribute to the heat transfer, flame temperature characteristics. It is seen from Table 7.4 that slightly higher O₂ is supplied in oxy-firing case compared to air-firing case. With the presence of higher O₂ in oxy-case, an increase in gas temperature is
expected. But a significant decrease in the gas temperature is observed. This can be explained on the basis of higher amount of H₂O and CO₂ fraction having higher heat capacity in the latter case. This dampens the characteristics of better oxidizing capability of O₂ in oxy-firing case.

The carbon monoxide (CO) and water vapour (H₂O) mass fraction (kg/kg) distribution in the direction of furnace length for all the cases considered in this study are presented in Figure 7.8. The contour in the top row of Figure 7.8 represents the CO mass fraction distribution for both the cases. The increase in the CO concentrations of the latter case was found. This is due to the lower gas temperature of the combustion cases and hence lower reaction rate of the CO oxidation. The gas temperature levels in the air-fired case affected the CO concentrations in the flame regions. The peak CO values expected in the flame region were conveyed by the lowest CO₂ values. The generation of CO mass fraction can be demonstrated by the mechanism of Boudouard reaction given in [96]. The figure in bottom row of Figure 7.8 represents the water vapour mass fraction (kg/kg) distribution for all the cases. It is seen from the figure that highest value of the water fraction is found in the furnace bottom. The coal-
water slurry particles are injected into the furnace which is further interacted with the furnace wall. Comparatively higher water vapour mass fraction is predicted in oxy-firing cases. This causes higher heat sink and lower temperature rise in oxy-firing case.

Figure 7.8: Carbon monoxide (CO), water vapor (H₂O) mass fraction (%) distribution for different cases.

Figure 7.9 characterizes the mass fraction of char particles in the reactor. Particle tracking mechanism represents that char particles are moving in the lower part of the reactor due to forces acting on it. The heated particles are burned in the later part of the furnace. The rapid reduction of oxygen concentration in the furnace negatively affected the oxidation of the residual char in the remaining part of the furnace. That’s why comparatively higher order of char fraction is predicted in oxy-firing case due lower reduction of O₂ as presented previously.
7.4.6. Variation of Slag Thickness and Flow Under Air/Oxy-fuel Condition

The main objective of this modelling was to develop an understanding of how the particles interact with the wall in the furnace. In order to achieve this, a number of sub-models were incorporated assuming different limitation under different operating conditions. The slag formation modelling was developed by combining solid fuel combustion and particles-wall interaction scheme coupled in a commercial CFD framework.

Figures 7.10-11 and Figures 7.12-13 show the slag thickness build-up in the transient calculation for air-firing and oxy-firing cases respectively. It is seen from these figures that the deposited layer of slag spreads over the furnace walls. Compared to other sides, significant fractions of layer were deposited in the lower wall. It is seen that the thickness of the deposited slag layer in the lower portion of the furnace was approximately 0-1.0 mm. This slag layer builds up due to deposition of the char particle on the furnace wall. When molten char/ash particles hit the furnace wall, based on the capturing criteria (see section 7.3.4), these particles are captured and deposited on the wall. Due to particle motion and the gravity effect, this newly formed molten slag layer is driven in the downwards direction. If the operating temperature is below the fusion temperature, a solid slag layer may be formed in between the molten slag layer and the wall. Compared to air-firing case, slightly higher fraction of slag layer is deposited in the oxy-firing case. It can also be seen that the slag
film is thicker at the lower part of the furnace due to the slag accumulation along its path; this is due to the lower char oxidation rate in oxy-firing case.

It would be useful to understand the dynamics of how the transient molten slag flows after the deposition on the furnace wall as the measurement of deposited layer thickness and flow behavior in a conventional way is difficult. Hence, this model provides a pattern of formation of slag layer and its flow characteristics to apply the developed model to a real life furnace by CFD. Figures 7.14-15 and Figures 7.16-17 show the slag surface velocity on the furnace wall respectively. As the furnace is horizontally placed at an inclination of 1.5°, so the molten slag moves towards the end of the furnace with time. When the particles deposited on the side wall, these slag flows down to the bottom of the furnace. The flow of the molten slag occurs due to gravity and momentum of the particle deposition. The slag possessed high viscosity and surface tension properties as can be seen from Table 7.2, hence the slag velocity is significantly lower than the gas velocity. It is found that the maximum slag velocity is approximately 0.0001m/s.
Figure 7.10: The slag thickness build-up in the transient calculation for air firing, (t=1.0 to 20 min)
Figure 7.11: The slag thickness build-up in the transient calculation for air firing, (t=30 to 60 mins)
Figure 7.12: The slag thickness build-up in the transient calculation for oxy-firing, (t=1.0 to 20 mins)
**Figure 7.13:** The slag thickness build-up in the transient calculation for oxy-firing, (t=30 to 60 mins)
Figure 7.14: The slag surface velocity (m/s) in air-firing, (t=1.0 to 20 mins)
Figure 7.15: The slag surface velocity (m/s) in air-firing, (t=30 to 60 mins)
Figure 7.16: The slag surface velocity (m/s) in oxy-firing, (t=1.0 to 20 mins)
Figure 7.17: The slag surface velocity (m/s) in oxy-firing, (t=30 to 60 mins)
7.5. Application of Slag Model in Large-scale Furnace

7.5.1. Physical Model and Combustion Scenario

In order to carry out slagging modelling in industrial furnace, a 550MWe tangentially-fired furnace located in Australia was considered. The details including dimensions, maximum operating conditions, unit productions of the utility furnace is summarised in Ref. [100]. The furnace considered in this study includes furnace hopper, several burners, water wall, hot gas off-take (HGOT) port, several accessories like, economiser, superheater, reheater and a bifurcation to air heater. The schematic diagram of the computational model for oxy-fuel combustion is presented in Figure 7.18. There are a total of eight mill-duct systems for four sides of the furnace. In this study, only five mills (1, 2, 5, 6, and 8 mills) are considered in operation and the rest are out of service (3, 4, and 7 mills) in order to maintain the similar operating conditions as in Ref. [100]. These duct and burner system consists of several burner’s secondary air duct (SAD) system, hot gas off-take (HGOT), inert burner and main burner. The position of different burners and secondary air duct system and the orientations are presented in Figure 7.18. Figure shows that each burner ports 1, 3, 5, and 7 were inclined by 24° while each of the remaining burner ports 2, 4, 6, and 8 were inclined by 30° with the perpendicular line to the furnace face.

In the present study, only coal combustion case under 29% oxy-fuel condition was considered based on the previous numerical work [14, 100]. The chemical and physical set up of the furnace and operating conditions of were entirely taken from furnace station data [340]. In this study, Victorian Brown coal is introduced as a fuel. The proximate and ultimate data of the used coal is summarized in Table 7.5. About 82% of the total fuel particles are introduced through main burner 66% of the gases are passed through the inert burner. The stoichiometric ratio equals to 1.18 was maintained. The distribution ratios of
$O_2/CO_2$ flow rates through different ducts is presented in Table 7.6. The particles are in the range of 0.01-1.5mm which was introduced as Rosin-Rammler distribution.

**Figure 7.18:** Physical model considered for large scale slagging combustion.
The inlet boundary condition of the present modelling is based on the outlet condition of the study in Ref. [342] which was used in mill duct system of the Loy Yang power station. In each burner, the fuel and gas were injected at a mass flow of 16.26 kg/s and 84.56 kg/s respectively. The secondary air was supplied through each mill-duct group uniformly at 120.79 kg/s. The mass flow rates and feed gas compositions (mainly includes O\textsubscript{2}, N\textsubscript{2}, CO\textsubscript{2}, H\textsubscript{2}O) through different burners for this study is presented in Table 7.7. The temperature of the burners and the secondary air duct systems were set to 397 K and 473 K respectively.

Major wall boundaries include furnace zone, water tube, convection zone, and round duct wall as shown in Refs. [86, 100]. Different convection zone such as reheater, economiser, superheater are set to the values of heat absorption of 121.98 MW, 100.0 MW and 115.75 MW respectively though a user defined sub coding. More details about the wall boundary data are given in Ref. [100]. The emissivity and temperature of the wall surfaces are set to be 0.71 and 973 K [92] respectively. In particle wall interaction modelling, Mundo-Sommerfield model [358] is assumed. In order to confirm steady transformation between laminar and turbulent quantities of the boundary layers, hybrid wall treatment is considered. Two outlets of the computational furnace such as bifurcation port and HGOTs were assumed. A zero gradient was applied in bifurcation port where an outward mass flow of 61.0 kg/s was applied for all the active HGOTs port. Based on the previous analysis [86, 100] on the same furnace, the grid system having 559,006 cells was chosen for the present the numerical analysis under oxy-firing condition.
Table 7.5: Fuel properties of Victorian Brown coal used in this study

<table>
<thead>
<tr>
<th>Properties</th>
<th>Coal</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Proximate analysis</strong></td>
<td></td>
</tr>
<tr>
<td>Volatile matter, % wt (db)</td>
<td>50.5</td>
</tr>
<tr>
<td>Ash content, % wt (db)</td>
<td>1.70</td>
</tr>
<tr>
<td>Fixed Carbon, % wt (db)</td>
<td>47.8</td>
</tr>
<tr>
<td>Moisture, % wt (ar)</td>
<td>62.0</td>
</tr>
<tr>
<td><strong>Ultimate analysis</strong></td>
<td></td>
</tr>
<tr>
<td>C content, % wt (ar)</td>
<td>67.7</td>
</tr>
<tr>
<td>H content, % wt (ar)</td>
<td>4.63</td>
</tr>
<tr>
<td>N content, % wt (ar)</td>
<td>0.52</td>
</tr>
<tr>
<td>S content, % wt (ar)</td>
<td>0.30</td>
</tr>
<tr>
<td>O content, % wt (ar)</td>
<td>24.9</td>
</tr>
<tr>
<td>GCV, MJ/kg</td>
<td>27.6</td>
</tr>
</tbody>
</table>

% wt (db)- dry basis, % wt (ar)- as received

Table 7.6: The mass flow rates (kg/s) O₂/CO₂ for the oxy-fuel combustion scenario at each secondary air duct.

<table>
<thead>
<tr>
<th>Secondary air duct</th>
<th>Distribution ratio (%)</th>
<th>Mass flow (kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper inert</td>
<td>5.00</td>
<td>4.96</td>
</tr>
<tr>
<td>Upper intermediate inert</td>
<td>5.00</td>
<td>4.96</td>
</tr>
<tr>
<td>Lower intermediate inert</td>
<td>5.00</td>
<td>4.96</td>
</tr>
<tr>
<td>Lower inert</td>
<td>5.00</td>
<td>4.96</td>
</tr>
<tr>
<td>Upper main</td>
<td>20.0</td>
<td>19.84</td>
</tr>
<tr>
<td>Upper core</td>
<td>6.67</td>
<td>6.61</td>
</tr>
<tr>
<td>Intermediate main</td>
<td>20.0</td>
<td>19.84</td>
</tr>
<tr>
<td>Intermediate core</td>
<td>6.67</td>
<td>6.61</td>
</tr>
<tr>
<td>Lower main</td>
<td>20.0</td>
<td>19.84</td>
</tr>
<tr>
<td>Lower core</td>
<td>6.67</td>
<td>6.61</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td>99.2</td>
</tr>
</tbody>
</table>
Table 7.7: The compositions of feed gases through the duct surfaces of inert and main burners for the oxy-fuel combustion scenario.

<table>
<thead>
<tr>
<th>Duct surface</th>
<th>Species concentrations (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$O_2$</td>
</tr>
<tr>
<td>UIB</td>
<td>2.00</td>
</tr>
<tr>
<td>IIB</td>
<td>2.00</td>
</tr>
<tr>
<td>LIB</td>
<td>2.00</td>
</tr>
<tr>
<td>UMB</td>
<td>11.51</td>
</tr>
<tr>
<td>IMB</td>
<td>12.00</td>
</tr>
<tr>
<td>LMB</td>
<td>11.78</td>
</tr>
</tbody>
</table>

Figure 7.19: Temperature distribution at different heights of the furnace.
7.5.2. *Flame Temperature and Gas Dynamics*

The flue gas temperature at different height of the furnace is presented in Figure 7.19. It is seen that the fuel mixes with the oxidizer in the burner area (Plane E and F) leading to higher flame temperature inside the furnace. This is due to possible reaction of highly volatile matters and the available oxygen. Compared to the main reaction zone, a decrease in the flame temperature is observed in the upper section of the furnace (Plane A-C).

*Figure 7.20: Velocity distribution at different heights of the furnace*
This is due to less O₂ and fuel compared to main reaction zone as can be seen from the O₂ distribution. It is also seen from the figure that compared to inert burner; slightly higher temperature is predicted in the main burner area. In oxy-firing, coal particles appeared to be combusted at a relatively higher rate in the near burner region and burn in situ because of enriched O₂ concentration. In the entire burner area, coal particles burn near to the main burner and inert burner region where the peak flame temperatures are observed.

**Figure 7.21:** O₂ mass fraction distribution at different heights of the furnace
Proper mixing of the coal/oxidizer is important for complete combustion. Hence, it is important to investigate the flow distribution in the computational area including main burner and inert burner region of the selected furnace. With the change of flow characteristics in different section of the tangential furnace, significant variation of the combustion performance is observed. For this study, oxidizer gas supplied to the furnace was 99.2 kg/s. Non-uniform flow distribution was predicted near the ducting system of 3, 4, and 7. This is due to out of service of those ducting system as mentioned earlier. For the present investigation in order to compare the outcome of the co-firing concepts with the only coal combustion results documented elsewhere [100]. Figure 7.20 presents the velocity distributions in different plane along the furnace height. A better flow mixing is observed in the burner area (plane E) which resulted better ignition leading to improved flame temperature. It is seen that comparatively lower flow is predicted in the upper plane (plane A-C) which is responsible for incomplete mixing. This can be verified by the temperature distributions on the respective plane as less temperature was predicted. This assured that flow velocity has direct influence on the combustion process.

7.5.3. **Species Level at Different Heights**

Figure 7.21 presents the $O_2$ mass fraction distributions (kg/kg) at different plane (A-F). Due to oxy-firing (OF-29) condition, higher $O_2$ concentrations was used through the secondary air ducts as inlet boundary condition, that’s why comparatively higher $O_2$ is observed near the burner region (plane E-F). The higher level of $O_2$ in the burner region corresponds to higher flame temperature. This can be seen from Figure 7.19. Similar findings have been observed in the modelling study of Nikolopoulos [16]. The $CO_2$ mass fraction distributions (kg/kg) in different plane along the height of the furnace are presented in Figure 7.22. The variations of $CO_2$ concentration in the upper planes of the furnace were uniform. But a significant variation was found near
the burner region due to aerodynamics of the flow and the continuous supply of CO₂ as recycled flue gas. While comparing with plane A and B, higher CO₂ is predicted in the plane E and F due to presence of enriched O₂ and better flow mixing leading to higher gas temperature. Similar changes were found elsewhere [86]. Maximum CO₂ concentrations were found in the main reaction zones.

![Full scale furnace view](image)

**Figure 7.22:** CO₂ mass fraction distribution at different heights of the furnace

This declaration is in line of with the ignition of flame temperature in the reaction zone. As soon as the devolatilization is completed, highly reactive char participated in the oxidation process with the surrounding O₂ leading to the formation of CO₂. Lowest CO₂ values observed in some planes were conveyed
by the highest CO values (not Shown here). According to Boudouard reaction, higher CO₂ concentration has a strong influence on the char oxidation leading to an increase in the CO concentrations in the reaction zone of the furnace. H₂O mass fraction distributions on the same planes were presented in Figure 7.23 for the combustion which can be explained as CO₂ and flame temperature distributions.

Figure 7.23: H₂O mass fraction distribution at different heights of the furnace

7.5.4. Slag Formation Behaviour and its Effect on Furnace Wall

One of the main objectives of the present study was to determine the slag formation characteristics in tangentially-fired furnace. A clear understanding of how the particles are interacted with the wall in the furnace is important for
industrial power plant. In this study, a validated CFD based slagging model is utilized to predict this phenomenon in a dedicated coal-based power plant. The slag formation modelling was developed by combining solid fuel combustion and particles-wall interaction scheme coupled in a commercial CFD framework.

**Figure 7.24:** Slag velocity (m/s) distribution on different side wall of the furnace, (at 60s)

It is very difficult to measure the slagging characteristics in a conventional power plant. It would be helpful to determine the dynamics of the deposition of the char component at elevated temperature in a dedicated coal-fired power plant. This study shows the transient deposition and flows of the slag on the vertical furnace walls. Hence, this model offers a trend of formation of slag layer and its flow characteristics considering a real life furnace by CFD. Figures
7.24-7.28 show the slag surface velocity on the four side of the vertical furnace wall. It is seen that the molten slag goes down towards the hopper zone of the furnace.

![Slag velocity distribution](image)

**Figure 7.25:** Slag velocity (m/s) distribution on different side wall of the furnace, (at 300s)

When the coals are introduced through the burners in the reaction zone, after devolatilization, rest of the char particles having temperature above the fusion temperature are interacted with the wall and some of these particles are captured. The deposited molten slag flows down due to gravity effect and the particle deposition momentum. The viscosity and surface tension of the slag is higher than normal coal. These properties play a vital role for lower slag flow.
In this study, maximum slag velocity was found in the range of 0-0.5 m/s. Figures 7.29-7.33 show the deposited slag thickness on different walls of the tangential furnace.

**Figure 7.26:** Slag velocity (m/s) distribution on different side wall of the furnace, (at 600s)

It was found that from these figures that the deposited layer of slag spreads over the lower part of the furnace walls. Comparatively thick slags are deposited around the burner and hopper region than the upper walls. It is predicted that the thickness of the deposited slag layer was approximately 0-1.0 mm. This slag layer builds up due to deposition of the char particle on the furnace wall. Because of the particle motion and the gravity effect, immediately
deposited molten slag layer is driven in the downwards direction. In the downward walls, temperature is below the fusion temperature resulting a layer of solid slag.

**Figure 7.27**: Slag velocity (m/s) distribution on different side wall of the furnace, (at 900 s)
Figure 7.28: Slag velocity (m/s) distribution on different side wall of the furnace, (at 1200 s)
Figure 7.29: Slag thickness (m) distribution on different side wall of the furnace, (at 60 s)
Figure 7.30: Slag thickness (m) distribution on different side wall of the furnace, (at 300 s)
Figure 7.31: Slag thickness (m) distribution on different side wall of the furnace, (at 600 s)
Figure 7.32: Slag thickness (m) distribution on different side wall of the furnace, (at 900 s)
The main objective of this chapter was to develop a comprehensive three-dimensional slagging combustion model in an industrial furnace. In order to achieve this, combination of coal combustion model with particle wall interaction model were coupled. This study was performed in two stages. Initial study was performed for validating the model considering a 3MWth small scale furnace. The slag flow and deposition characteristics were evaluated and compared with the available data. The slag thickness deposited on the furnace wall was found in the range of 0-1.0 mm which was reasonably in good agreement with the available data.
agreement with the available data. The slag surface velocity was found approximately 0.1 mm/s. Transient build-up of the slag thickness with slag surface velocity were illustrated considering air and oxy-firing cases. Comparatively higher fraction of slag layer was predicted due to incomplete combustion of the char component. Later, the validated slagging model was applied in a 550MWth tangentially fired furnace considering Brown coal combustion under oxy-fuel condition. The deposited molten slag flows down due to gravity effect and the particle deposition momentum. It was seen that the molten slag goes down towards the hopper zone of the furnace. In this study, maximum slag velocity was found in the range of 0-0.5 mm/s.
CHAPTER 8. Summary and Recommendations

8.1. Summary of the Research Work

In this thesis, a comprehensive computational fluid dynamics (CFD) model has been developed and validated to investigate the combustion phenomenon of solid fuels such as coal and biomass (Shea meal, straw and wood) and slag formation behaviour in different furnaces. This numerical investigation have been carried out to provide a guideline for combustion of different irregular shaped biomass fuels having larger aspect ratios under different combustion environments such as air-firing and oxy-firing cases based on the experimental data. The observation of this research also can provide useful understanding to the slag formation characteristics on the refractory wall in an industrial furnace. Overall, there are a number of specific objectives of the present research and following sections will discuss individually.

The first main objective of the present research work was to develop a complete three dimensional CFD model to examine the radiative and convective heat transfer performance and burnout effect considering the combustion of Russian coal in air-firing and three different RFG based combustion cases. A commercial CFD package AVL Fire ver. 2009.2 coupled with the mathematical models related to combustion of solid fuels with proper kinetics parameter prescribed for the devolatilization and char combustion was used. In different combustion cases, radiative heat transfer was predicted and compared with the available experimental data. The numerically calculated results showed a reasonable agreement against the measured radiative heat flux on the furnace radiative wall. Different combustion cases were further illustrated presenting and discussing on the basis of temperature distribution, species concentration.
distribution, and velocity distribution in the furnace. Flame stability had been confirmed using the aerodynamic effects of primary and secondary inlets of the burner in the IFRF burner. The numerical results showed that the flame for the RFG fired case was relatively concentrated in the central position compared to air-fired flame. There was understandable combustion delay in RFG fired combustion compared to air-fired case. Results showed that the flame temperature distribution and O$_2$ concentration of RR75 combustion case were similar to the air-fired case. Also, highest peak radiative heat flux and highest flame temperature with confined structure corresponded to the lowest recycle ratio of RR 65%. The flame temperature of RR65 % was higher, and the flame structure was shorter and more confined. For retrofitting purpose, a working range for the selected fuel under different cases was developed. From the presented working range, air equivalent radiative heat flux observed at a RR of 71% where convective heat flux increases as the radiative heat flux goes downstream with the increase of RR. Air equivalent flame temperature was found to be at RR of 72 %. While predicting the carbon in ash, reasonable agreement was observed when compared with the experimental data. Burnout improved under oxy-fuel firing conditions compared to air combustion. Considering global climate change and the emission of CO$_2$ from power plant, this RFG based combustion study represents the platform for the reduction of CO$_2$ from solid fuel combustors. The present study provides the confidence to develop the model for the co-combustion of coal and biomass under oxy-fuel conditions. The next step of the study was to focus on the co-combustion of biomass particle with the coal for oxy-fuel combustion technique, which may be implemented to the existing or coal based power stations.

The second main objective of the research work was to develop and validate a three dimensional CFD modelling for co-firing of coal with biomass sharing (20% and 40%) under different oxy-fired operating conditions. The model
developed for coal combustion modelling in previous study was modified for using multiple fuels (coal and biomass) having different properties and sizes. User defined subroutines were coupled with the used code for considering the aerodynamic behaviour of irregular shaped biomass particles. In order to attain confidence, a validation against experimentally measured radiative heat flux was performed. In most of the cases, numerical results were found within 5% variation with the experimental results. It was found that the increase of biomass sharing was responsible for increasing the volume of the flame shape, but the peak temperature decreased. Finally air equivalent peak flame temperature and peak radiative heat flux were observed at the RR of 71% and 70% for 20% and 40% biomass sharing respectively. Comparatively improved burnout was observed in oxy-fuel cases with higher biomass sharing. Overall, this study provided the confidence to predict the co-combustion of coal and biomass in oxy-fuel conditions.

The third main objective was to implement the developed co-firing model for the combustion of irregular shaped straw particles having larger aspect ratios under air to oxy-firing combustion environments in a small scale furnace. Three different oxy-fuel cases such as OF25%, OF30% and OF35% were investigated with respect to flow and species distributions, flame temperature profiles, and emissions. A critical analysis suggested that an inlet oxygen concentration of 30% would yield a match between air-firing case and oxy-fuel cases. The effect of fuel switching from coal to straw was evaluated by comparing the co-firing cases considered. It is seen that 20% sharing of straw does not significantly change the temperature profile compared to 100% coal firing. With the increase of straw contribution, flame temperature is decreased. The higher level of CO is observed for 100% straw burning case. This was due to increasing importance of increased residence time on the burnout for increasing fuel straw share. Improved burnout under oxy-fuel firing conditions was observed compared to
air combustion for different biomass sharing cases. Also the heating profile considering different sizes of straw particles were predicted.

The fourth main objective of the present research work was to scrutinize the performance of co-firing concept of pulverized coal and irregular shaped biomass particles (woody type) in a 550 MWth tangentially fired furnace. For this purpose, a series of investigations were carried out combining three different biomass sharing (20%, 40% and 60%) cases under four different combustion environments (air firing, OF 25, OF 27 and OF 29). Different oxy-fuel cases were evaluated based on Chalmers’ approach. Compared to the pure coal combustion, a significant decrease in the flame temperatures with the increase of biomass particle flow was predicted. Relationship between the air-firing to oxy-firing cases was presented on the basis of peak flame temperature for retrofitting purpose. It was found that the increase of biomass sharing was responsible for increasing the flame volume while the peak flame temperature decreases. Comparatively improved burnout was observed in oxy-firing cases. The amount of unburned carbon in ash was predicted to increase when cofiring ratio increase due to the large size of the biomass particles. This study highlighted the possible impact of changing the fuel ratio and combustion atmosphere on the boiler performance, underlining that minor redesign may be necessary when converting to biomass co-firing under air and oxy-fuel conditions.

The final objective of the present research work was to develop a comprehensive three dimensional slagging combustion model in an industrial furnace. In order to achieve this, combination of coal combustion model with particle wall interaction model were coupled. This study was performed in two stages. Initial study was performed for validating the model considering a 3MWth small scale furnace. The slag flow and deposition characteristics were
evaluated and compared with the available data. The slag thickness deposited on the furnace wall was found in the range of 0-1.0 mm which was reasonably in good agreement with the available data. The slag surface velocity was found approximately 0.1 mm/s. Transient build-up of the slag thickness with slag surface velocity were illustrated considering air and oxy-firing cases. Comparatively higher fraction of slag layer was predicted due to incomplete combustion of the char component. Later, the validated slagging model was applied in a 550MWth tangentially fired furnace considering Brown coal combustion under oxy-fuel condition. The deposited molten slag flows down due to gravity effect and the particle deposition momentum. It was seen that the molten slag goes down towards the hopper zone of the furnace. In this study, maximum slag velocity was found in the range of 0-0.5 mm/s.

8.2. Recommendation for Future Work

Several recommendations are now made for future work to extend the completed research. This recommendation aim to create better understanding of the development and validation of the combustion models in different types of furnaces. The recommendations are summarized below:

The char combustion was modelled in this study by a global reaction of order unity due to the complexity of carbon-oxygen reaction scheme. This model cannot accurately capture the effect of the temperature and $O_2$ partial pressure dependency on the $C/CO_2$ production rate and char reaction kinetics. The enhanced three-step semi-global kinetics model is important and needs to be used to yield intrinsic kinetics data over a range of complex oxy-fuel conditions.
The numerical simulation of the mean chemical reaction rates of the fuel has been considered to be a main problem in the determination of chemical kinetic processes. This is due to reaction rate being non-linear functions of the local temperature values and the species concentrations. Detailed chemical kinetic mechanisms with the appropriate kinetic parameters of the chemical balance equations are better to use in the simulation of the fuel reaction process.

The modified turbulent controlled combustion model, the Eddy Breakup Model was used to calculate the mean reactions rate for the combustion simulation. More sophisticated models are available to achieve that purpose such as Turbulent flame Speed Closure Combustion Model (TFSCM), Eddy Dissipation model (EDM), Probability density function (PDF).

On the furnace wall surface, the effect of upstream burner geometry was partially taken into consideration in this numerical modelling. An incorporating of a full scale upstream mill ducting on the large scale tangentially-fired furnace can provide accurate gas and particle phase boundary conditions at the burner exit plane and has a great importance in establishing the efficient mixing within the furnace. The developed model can be further extended to include the prediction of further research in regards to the scrubbing process of CO2 from the power plant and new design optimisation of the boiler.

Co-firing of solid recovered fuel with coal can be implemented by modifying the developed model. In order to overcome the difficulties of the complex, non-homogeneous nature of the waste recovered fuel, the biogenic and plastics form can be considered as a mixture of two different fractions. Hence the implementation of co-firing model for any type of biomass based fuel is applicable.
In this research, a simplified slag flow and deposition model was developed for industrial furnace. Further development of the present model is suggested considering detailed char/ash particle capture, slag flow and wall burning sub-process. The main limitation of the present slagging model was the deposition of lower slag thickness which can be further modified for a real life furnace. Further modification is needed for application of slagging model for biomass co-firing process.
CHAPTER 9. References and Appendix

9.1. References


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