CFD Modelling of Dry Slag Granulation Using a Novel Spinning Disc Process

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Slags generated in metallurgical industry are high volume by-products or wastes containing a large amount of heat. In blast furnace ironmaking, for example, for every tonne of hot metal produced, about 300 kg of slag is generated. The cooling of molten slag to ambient temperature can release up to 1.8 GJ/t of thermal energy. Blast furnace slags are currently either water granulated or air cooled. Water granulation is commonly adopted to produce glassy granules that can be used for cement production. However, such slag treatment methods have some obvious shortcomings: ie, no heat recovery, air pollution, and consumption of a large amount of fresh water. Therefore, there has been an increasing interest in processing molten slags without using water quenching, so-called dry slag granulation (DSG).

CSIRO is developing a novel DSG process based on a spinning disc technology [1-4]. This process utilises centrifugal force to break up a molten slag stream into droplets, which are quenched by cold air and solidified into glassy granules for cement manufacture. The process is also able to recover the sensible slag heat as hot air. The integrated DSG and heat recovery process has been successfully demonstrated at a pilot plant scale with throughputs of up to 5 t/h (Figure 1).

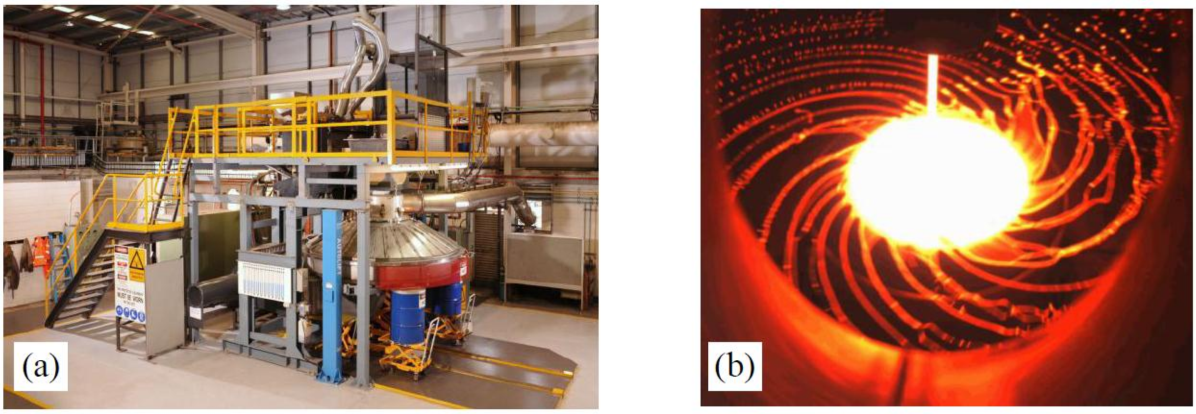

Figure 1: Photos of (a) the semi-industrial scale (3 m diameter) integrated DSG and heat recovery pilot plant at CSIRO Clayton laboratory and (b) a typical still image from high speed video recording of the slag atomisation by a spinning disc in CSIRO's DSG process.

CFD models, developed using commercial ANSYS CFX package [5], have been used to simulate the various complex and dynamic physical steps in the DSG process. These steps include: slag spreading on the spinning disc, slag film breakup after leaving the disc, slag droplet formation, droplet collision with walls, air flow and interaction of air with slag droplets/granules as well as droplet quenching and heat exchange. CFD modelling has played a key role in process design, optimisation and scale up. This presentation provides a brief overview of CFD modelling work on slag atomisation by a spinning disc. The work uses two multiphase CFD models: a steady-state two-dimensional (2D) model for molten slag spreading on the disc [6] and a transient three-dimensional (3D) model for the breakup of the slag film and droplet formation [7]. Moreover, the 2D model was also utilised in a numerical experiment that was designed based on a fractional-factorial approach and dimensional analysis. This produced a dimensionless correlation that can be used for guiding the DSG operation, process optimisation and scale-up with potential applications to a wider variety of atomisation systems using spinning discs [8].

One important objective of the 2D model is to predict the free surface profile of the liquid slag, from which one can estimate the thickness of the slag film at the disc edge prior to it breaking up into droplets. Figure 2 shows typical results from the 2D model, where Figure 2(a) illustrates the predicted free surface profile as indicated by an interface between the liquid slag (red-region) and air (blue-region), while Figure 2(b) and Figure 2(c) depict the predicted flow and temperature fields, respectively. The model is also capable of predicting the formation of a solid slag layer due to heat transfer; this is marked in Figure 2(a) and Figure 2(b). The predicted slag film thickness at the disc edge, and other properties, are used as input to a 3D model to predict the breakup of the thin slag film into ligaments and finally the formation of droplets.

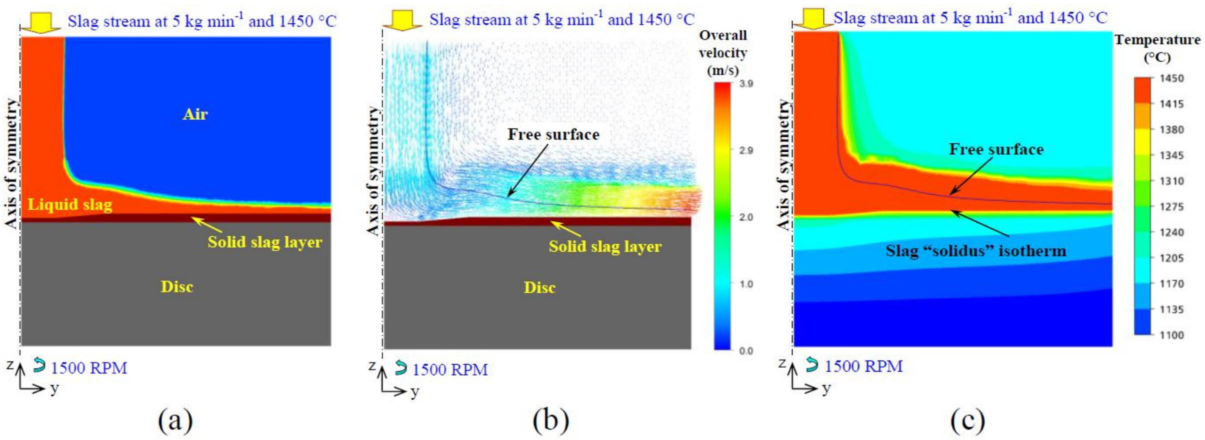

Figure 2: Typical predictions by 2D CFD model: (a) Free surface and solid slag layer profiles, (b) Flow field, and (c) Temperature fields in fluid and solid regions.

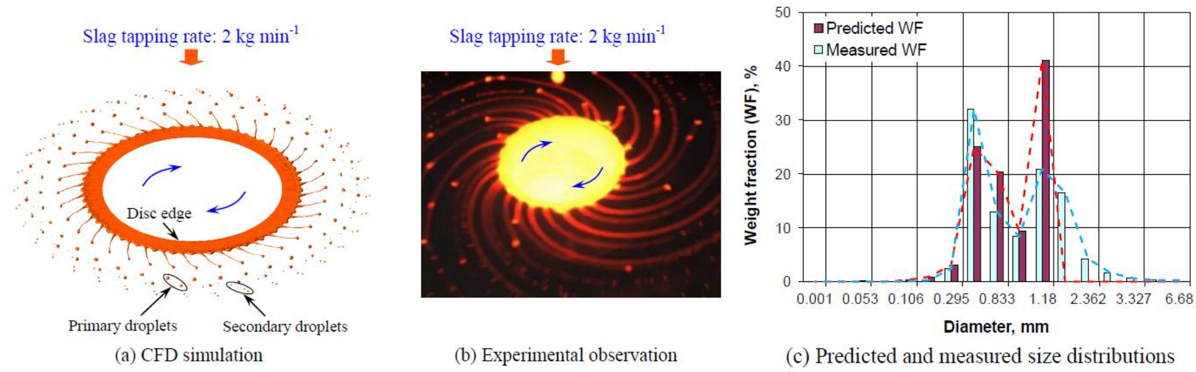

Figure 3: Comparison between CFD simulation and experimental observation on liquid slag breakup by a spinning disc, formation of ligaments and droplets, and droplet and granule size distributions (Liquid slag tapping rate: 2 kg min^{-1}, Disc spinning speed: 1780 RPM) [7].

Figure 3(a) illustrates the process of liquid slag film being broken up into ligaments and droplets by a spinning disc as predicted by the 3D model. Also shown for comparison is a high-speed video image obtained from an experiment (Figure 3(b)). Figure 3(c) gives predicted droplet size distribution in comparison with measured granule size distribution.

It can be seen from Figure 3 that the model qualitatively captures key features of the ligament formation and subsequent breakup processes which were observed in the experiment (Figure 3(a) and Figure 3(b)). From this modelling result one can further evaluate the slag droplet size distribution (Figure 3(c)), which is indicative of potential slag-air heat exchange efficiency and quality of the slag granules as well as the quantitative validity of the model.

Furthermore, by performing a parametric numerical experiment with the 2D model and by means of dimensional analysis and a fractional factorial design approach proposed by Box and Behnken's [9], a dimensionless correlation between the slag film thickness and the important influencing parameters was obtained as [8]

$$\frac{h}{R} = 0.479\left(\frac{\rho\Omega R^2}{\mu}\right)^{-0.612}\left(\frac{\mu R}{G}\right)^{-0.336} \qquad (1)$$

where, G is the liquid tapping rate (kg s^{-1}); Ω the disc spinning speed (rad s^{-1}); R the disc radius (m); μ the liquid viscosity (Pa s); ρ the liquid density (kg m^{-3}); and h the liquid film thickness at the disc edge (m).

Within the parameter ranges investigated, Eq. (1) can be used to evaluate appropriate operating and design conditions for producing a liquid film of desired thicknesses suitable for atomising different liquids by spinning discs. For instance, Figure 4 shows a relationship between slag tapping rate and disc spinning speed for maintaining different slag film thickness at the disc edge as implied by Eq. (1). This figure indicates that, for example, in order to keep a film thickness at 0.5 mm the disc spinning speed should be set at 1750 RPM to process liquid slag tapped at a rate of 5 kg min^{-1}.

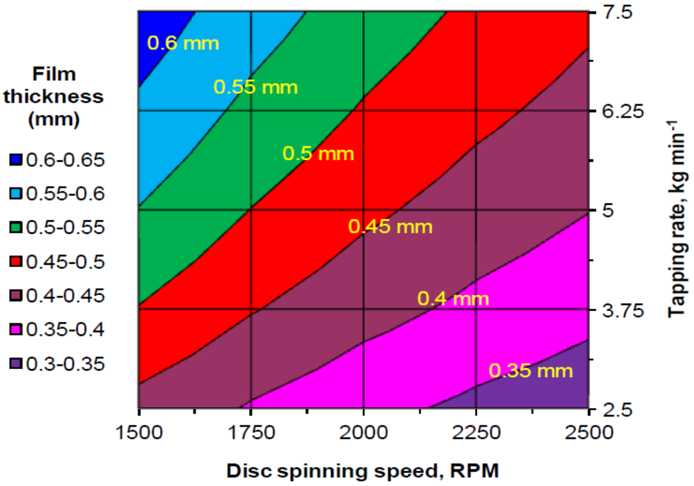

Figure 4: Predicted relationship between slag tapping rate and disc spinning speed for maintaining different film thickness (Disc radius: 25 mm, Liquid slag viscosity: 0.7 Pa s, Liquid slag density: 2590 kg m^{-3}).

In summary, CFD modelling has played a key role in the design, operation and scale up of CSIRO's dry slag granulation process. The 2D CFD model can be used to give timely predictions that allow one to explore and select appropriate design and operating conditions for producing a slag film that will ultimately break up into droplets of desired size; and the 3D CFD model can then be applied to predict the size distribution of these droplets. The relatively efficient nature of the 2D model also allows one to perform virtual (numerical) experiments on multiple parameters (i.e. without doing time-consuming and costly experiments in laboratory) so as to establish dimensionless correlations that can be used for optimising and scaling up the DSG process. In addition, the 3D model can be extended to simulate liquid film breakup, droplet formation, droplet motion and deformation at the wall during collisions. This potentially can be applied to provide an in-depth understanding of the entire liquid atomisation process that is based on spinning discs.

ACKNOWLEDGEMENTS

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