The Development and Evaluation of New Microwave Equipment 
and its Suitability for Wood Modification

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Abstract

The present research offers an assessment of the computer modelling process for developing new microwave equipment suitable for wood modification. To understand the functioning of the new projected microwave equipment and moreover, to make its operability as safety as required by the Australian and International Safety Organization, the computer modelling process was completed by developing the customised devices, setting the appropriate testing procedures and measuring the specific parameters.

Initially, the fundamentals of microwave heating including the history of utilisation of these technologies, electromagnetic theory, details about volumetric and selective heating, and also basics regarding microwave heating of the wood are examined.

Subsequently, an insight into the main microwave systems components and current developments in the industrial microwave heating is provided. The overview report ends with details about the expansion of computerized numerical microwave modeling techniques and comments about some of their relevant features.

A practical and innovative way able to control the intensity and distribution of the microwave energy and to enhance the microwave treatment pattern within dielectric is then presented. It was accomplished through computerized 3D electromagnetic simulations and validated using pilot plant microwave equipment.

To complement the microwave applicator to highly reduce the energy reflection towards the generators, a novel idea is put forward. The experimental tests show that the reflected energy can be reduced up to 50%.

A custom-designed microwave leakage suppression device for wood treatment in continuous flow microwave industrial systems presented together with its evaluation completes the research work.

Finally, the importance of the research, the key facts and the recommendations for further work are emphasized.

Keywords: microwave heating processes, electromagnetic modelling and simulations, applicators, microwave leakage suppressor device, wood modification
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I would like to thank my parents for their continuous moral support despite the distance which separated us, and also I would like to thank my wife Georgiana for her unfailing support.
DECLARATION

This thesis contains no material which has been accepted for the award of any other degree or diploma, except where due reference is made in the text of the thesis. To the best of my knowledge contains no material previously published or written by another person except where due reference is made in the text of the thesis.

Signed: Mihai Stelian Daian

Dated: May 2006
PART I LITERATURE REVIEW

CHAPTER 1: MICROWAVE PROCESSING OF WOOD ......................... 5
  1.1 Microwave Heating - History and Applications .................. 5
  1.2 Theory Behind the Microwave Heating .......................... 6
    1.2.1 Maxwell’s equations and electromagnetic waves .......... 7
    1.2.2 Volumetric and Selective Heating ......................... 10
  1.3 Microwave Heating Process of Wood .............................. 13
    1.3.1 Dielectric response of wood .................................. 14
    1.3.2 Physical model of microwave heating of wood ........... 15
    1.3.3 Microwave drying of wood - the response to its physical characteristics 16

CHAPTER 2: MICROWAVE SYSTEMS ............................................. 20
  2.1 Microwave Generators .................................................. 20
  2.2 Transmission Lines ....................................................... 25
    2.2.1 Reflection and transmission parameters ................... 32
    2.2.2 Fresnel reflection and transmission coefficients ........ 35
  2.3 Microwave Applicators ................................................ 38
    2.3.1 Single-mode applicators ....................................... 38
    2.3.2 Multimode applicators ......................................... 41
  2.4 Microwave Systems’ Design Parameters ......................... 41
    2.4.1 Heating uniformity .............................................. 42
    2.4.2 Required microwave power .................................... 43
    2.4.3 Applicator size .................................................. 43
    2.4.4 Microwave suppressors ....................................... 44
  2.5 Operational Health and Safety Measures – Microwave Safety Standards ..... 47
  2.6 Suppressors/Choke Systems & Other Materials and Devices Related to Microwave Leakage Suppression and Microwave Leakage Prevention ................. 50
CHAPTER 3: CURRENT DEVELOPMENT OF THE INDUSTRIAL MICROWAVE HEATING TECHNOLOGIES WORLDWIDE

3.1 Serpentine Microwave Drying of Webs and Sheets

3.2 Microwave Drying of Regular Geometric Shapes: Blocks, Slabs, and Beds of Particles

3.3 Batch Ovens

3.4 Continuous Ovens

3.5 Microwaves Vacuum Dryers

3.6 Microwave Equipment for Wood Modification and Treatment
   3.6.1 Growth stress relief in timbers
   3.6.2 Microwave modification of wood to assist wood drying
   3.6.3 Microwave timber modification for preservative treatment
   3.6.4 Microwave modified solid wood products
   3.6.5 The Tunnel Applicator
   3.6.6 The Rotary Applicator
   3.6.7 The Box Applicator
   3.6.8 The Taper Applicator
   3.6.9 Intermediate sized conveyor

CHAPTER 4: ELECTROMAGNETIC MODELLING OF MICROWAVE EQUIPMENT AND PROCESSES

4.1 Introduction

4.2 Development of Computerized Numerical Microwave Modeling

4.3 E-Field 3-D Modeling and Simulation Techniques

4.4 Software Database

4.5 CST Microwave Studio - the Chosen EM Modeling Package
   4.5.1 CST MWS features and benefits
   4.5.2 CST MWS features summary

PART II   RESEARCH METHODOLOGY, DEVELOPMENT OF MICROWAVE EQUIPMENT AND THE SUITABILITY TESTS FOR WOOD MODIFICATION

CHAPTER 5: RESEARCH METHODOLOGY

5.1 Defining the Research Problem and Objectives

5.2 Approach to the Research Problem

CHAPTER 6: COMPUTER MODELLING OF THE ENERGY DISTRIBUTION WITHIN WOOD THROUGHOUT MICROWAVE PROCESSING

6.1 Introduction

6.2 Simulation and Optimisation of the Energy Distribution within Wood, Generated by Different Size Applicators

6.3 Experimental Trials Based on Modelling Results

6.4 Conclusions
List of Figures

Figure 1: Propagation of a plane wave ................................................................. 8
Figure 2: Electromagnetic spectrum and frequencies used in microwave processing ...... 9
Figure 3: Exponential decay of the electric field in a lossy dielectric .................. 11
Figure 4: The potential of microwave applications in wood industry ................... 13
Figure 5: Physical model of microwave heating of wood .................................. 16
Figure 6: Principal directions on wood stem ...................................................... 17
Figure 7: Microwave drying periods for wood .................................................. 19
Figure 8: Microwave tube development ............................................................ 21
Figure 9: Power-frequency limits of microwave generators .............................. 22
Figure 10: Schematic diagram of a magnetron shown in cross-section ............... 23
Figure 11: Cross-section of a magnetron ............................................................ 24
Figure 12: 2.45 GHz magnetron ........................................................................ 24
Figure 13: Equivalent circuit of a transmission line .......................................... 25
Figure 14: Waveguides - TEM, TE, and TM waves ......................................... 26
Figure 15: Waveguide types ............................................................................ 26
Figure 16: Field distributions and key expressions of calculation for modes in rectangular waveguides ................................................................. 28
Figure 17: Field distributions and key expressions of calculation for modes in cylindrical waveguides ................................................................. 29
Figure 18: Coaxial transmission line .................................................................. 31
Figure 19: Field distributions in coaxial line ...................................................... 31
Figure 20: Definition of the two-port network ................................................... 32
Figure 21: S-parameters .................................................................................... 33
Figure 22: Measuring S-parameters ................................................................. 33
Figure 23: Familiar forms of the reflection/transmission parameters ................. 34
Figure 24: Reflection parameters ................................................................. 34
Figure 25: Transmission parameters ............................................................. 35
Figure 26: Reflected and transmitted electric field diagram ............................. 35
Figure 27: Single-mode applicators .............................................................. 40
Figure 28: Schematic of leakage suppression approaches ............................... 46
Figure 29: Schematic representation of a microwave conveyorised system fitted with leakage suppression devices ....................................................... 48
Figure 30: Australian standard AS2772.1-1990 radio frequency radiation ........... 49
Figure 31: Cross section of idealised corrugated choke.................................... 51
Figure 32: United States Patent No. 4,227,063 ................................................. 53
Figure 33: United States Patent No 4,182,946 ................................................... 55
Figure 34: Serpentine microwave drying of webs and sheets Error! Bookmark not defined.
Figure 35: Meander/Serpentine microwave waveguide. Error! Bookmark not defined.
Figure 36: Microwave oven for drying of regular geometrical shapes Error! Bookmark not defined.
Figure 37: Batch oven .............................................................. Error! Bookmark not defined.
Figure 38: Continuous multimode microwave oven ..... Error! Bookmark not defined.
Figure 39: Continuous multimode oven with several magnetrons - Raytheon ...... Error! Bookmark not defined.
Figure 40: Continuous microwave belt oven ................. Error! Bookmark not defined.
Figure 41: Continuous oven – Microdry ......................... Error! Bookmark not defined.
Figure 42: Continuous multimode transverse E field oven – Magnetronics Ltd. ... Error! Bookmark not defined.
Figure 43: Continuous microwave dryer/heater ............. Error! Bookmark not defined.
Figure 63: Schematically representation of the basic water trap device......................135

Figure 64: a) Cylindrical applicator with cavities containing absorbing materials; b) Measurement equipment setup.................................................................138

Figure 65: Attenuation obtained using ARC microwave absorbing material...........139

Figure 66: Water trap-microwave leakage suppressor a) computer modelling variant; b) built variant ........................................................................................................141

Figure 67: Experimental setup of the water trap-microwave leakage suppressor ......142

Figure 68: Modelling of band stop filter devices: a) 43x86 mm applicator and S11/S21 results; b) 150x150 mm applicator and surface current (peak) images .................144

Figure 69: Microwave reflective device ........................................................................146

Figure 70: The combined water trap-reflecting device.................................................146

Figure 71: Graphical representation of water trap reflective device - computer modelling: a) view of water absorbing tubes, b) view of absorbing cavities.............148

Figure 72: Tests of microwave suppressor with included metal flaps.........................149

Figure 73: Generator status during the tests.................................................................150
List of Tables

Table 1: Modern modeling software applicable to simulation of the test problems, as of September 2001 ..............................................................................................................86

Table 2: CST MWS Software development history ......................................................91

Table 3: Gamma values for the microwave applicator having a piece of moist timber inside .............................................................................................................................132

Table 4: Microwave absorbing materials......................................................................136
Nomenclature

\( a_1, a_2 \) Incident waves

\( \mathbf{B} \) Magnetic field [T]

\( b_1, b_2 \) Reflected waves

\( c \) Speed of light in free space (= 2.99792458 \times 10^8 \text{ m/s})

\( \mathbf{D} \) Electric flux density [C/m²]

\( D_p \) Penetration depth [m]

\( \mathbf{E} \) Electric field strength [V/m]

\( f \) Oscillation frequency of the fields at a given point in space [Hz]

\( \mathbf{H} \) Magnetic field intensity [A/m]

\( I \) Current [A]

\( \mathbf{J} \) Current density [A/m²]

\( P_{\text{abs}} \) Absorbed power

\( P_{\text{out}} \) Output power from the source

\( P_z \) The energy at a distance \( z \) away from the source

\( Q \) Quality factor

\( S_{11}, S_{22} \) Reflection scattering parameters (S-parameters)

\( S_{12}, S_{21} \) Transmission scattering parameters (S-parameters)

\( \delta \) Transmission coefficient. Chapter 2

\( t \) Time [s]

\( \tan \delta \) Loss tangent

\( Z_0 \) Characteristic impedance[Ω]

\( Z_L \) Load impedance [Ω]

\( Z_{TE} \) Wave impedance for TE waves

\( Z_{TM} \) Wave impedance for TE waves

\( \varepsilon_0 \) Permittivity of free space (= 8.854 \times 10^{-12} \text{ C}^2/\text{N·m}^2)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>$\varepsilon'$</td>
<td>Dielectric constant of the dielectric medium</td>
</tr>
<tr>
<td>$\varepsilon''$</td>
<td>Dielectric loss factor</td>
</tr>
<tr>
<td>$\Phi$</td>
<td>Phase of the transmission coefficient [rad]</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>Reflection coefficient</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Wavelength (the distance between successive wave crests)</td>
</tr>
<tr>
<td>$\lambda_0$</td>
<td>Wavelength in free space ($= 0.122 \text{m}$)</td>
</tr>
<tr>
<td>$\lambda_s$</td>
<td>Wavelength in waveguide [m]</td>
</tr>
<tr>
<td>$\mu_0$</td>
<td>Permeability of free space ($= 4\pi \times 10^{-7} \text{Wb/A} \cdot \text{m}$)</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Magnitude of the reflection coefficient</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Magnitude of the transmission coefficient</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Angular frequency [rad/s]</td>
</tr>
</tbody>
</table>

**Abbreviations**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>DUT</td>
<td>Device under test</td>
</tr>
<tr>
<td>EM</td>
<td>Electro-Magnetic</td>
</tr>
<tr>
<td>FSP</td>
<td>Fiber saturation point (%)</td>
</tr>
<tr>
<td>MW</td>
<td>Microwave</td>
</tr>
<tr>
<td>RL</td>
<td>Power loss</td>
</tr>
<tr>
<td>TE</td>
<td>Transverse electric waves</td>
</tr>
<tr>
<td>TEM</td>
<td>Transverse electromagnetic waves</td>
</tr>
<tr>
<td>TM</td>
<td>Transverse magnetic waves</td>
</tr>
<tr>
<td>VSWR</td>
<td>Voltage Standing Wave Ratio</td>
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Introduction

The use of microwave processing techniques in wood production is still a novel and revolutionary concept. High intensity microwave treatment creates changes in wood structure, which might significantly contribute to the development needs of timber industry by accelerating wood drying time, relieving the growth stresses, facilitating preservative impregnation and enabling the production of solid wood products. This is possible due to the increased life span and strength of wood structure after it is microwaved.

The microwave drying process can reduce drying times by up to 12 months by replacing the need for steam conditioning following kiln drying (i.e. microwave conditioning can enable immediate kiln drying of green timber). On the other hand, the impregnation of wood with preservatives and resins following microwave modification can result in woods products suitable for a wide range of applications such as poles or posts and will be protective against fungal degradation or termites.

It is predicted that microwave irradiation can relieve growth stresses in fast grown plantation hardwoods such as Blue Gum and other Eucalypts. This leads to an enhanced wood value. For example, plantation hardwoods could be produced as high-value sawn timber as opposed to low-value chipped wood.

Starting from these considerations and strongly based on two internationally patented technologies, TORGVIN and VINTORG\textsuperscript{1}, the present research was conducted with a particular emphasis on the design and evaluation of new microwave equipment. The main aim was to further develop the existent microwave applications and the use of microwave technology for timber processing.

\textsuperscript{1} United States Patents No. 6.596.975, Vinden et al., July 22, 2003
Microwave wood modification requires the application of very intensive microwave energy (up to 30 kW/cm²) for very short periods. To achieve such a high intensity and to ensure its subsequent release in the wood, the development of new equipment (i.e. applicators) utilising a range of different frequencies (915 MHz and 2.45 GHz) plays one of the most important role in any microwave research program.

Currently, the microwave wood modification techniques are at their early development stages. Because, no microwave equipment available on the market and used for other applications is suitable for microwave processing of wood, customised equipment (i.e. applicators and suppressors) has to be designed, tested and manufactured. Moreover, different wood applications such as boards, round logs or blocks treatment, imposes not only the development of new applicators but also the creation of water dummy-loads and microwave leakage suppression devices. They have to be operational under Australian and international radiation regulations.

To optimise and minimise the project design engineers’ work, modelling and simulation of the microwave energy interaction with wood material represents an indispensable tool. From economical point of view, the industry solicits a good utilisation of the energy and practical ways to get the best results from the newest microwave technology.

Accordingly, the main theme of the current research is the development of new equipment (applicators and suppressors) utilising a range of different frequencies (915 MHz and 2.45 GHz) to achieve high electromagnetic intensity and to ensure its subsequent release in the wood.

First of all, in order to optimise and control the microwave wood modification process, a good understanding of the various phenomena involved is needed. This understanding is achieved by modelling, simulations, and experimental measurements. Therefore, the main objectives taken on to be accomplished within this research are:

- Perform modelling and simulation of the microwave energy interaction with wood material by inventing and using different technical structural and dimensional arrangements of the microwave equipment.
- Decide on the optimum equipment configuration and collaborate to physically build it.
• Test and validate the suitability of the developed equipment for microwave wood modification.

This thesis is divided into two parts, each of them comprising of four and five chapters, respectively. The first part represents the basic theory and the research tools that were used in the course of this research. Chapter one gives an overview of the microwave processing of wood. Chapter two provides an insight into the characterisation of the microwave systems components such as: microwave generators, transmission lines, applicators and microwave leakage suppressors. Other issues highlighted here are the main parameters involved in microwave heating processes (i.e. absorbed power, reflection and transmission parameters, etc.). Finally, at the end of this chapter, the operational health and safety measures are presented. Chapter three and four emphasise the current development of the microwave industry and the availability of the most popular electromagnetic modelling software.

The second part provides the quantitative research of this project. Chapter five brings up the research approach and methodology. Thereafter, chapter six, seven and eight focus on the development of new microwave equipment and the evaluation of its suitability for wood modification. Chapter nine, which completes the study, emphasises the importance of this research to the timber industry, the key results and few suggestions for the future work.
PART I

LITERATURE REVIEW
CHAPTER 1
MICROWAVE PROCESSING OF WOOD

1.1 Microwave Heating - History and Applications

For the first time, microwaves were controlled and used during the Second World War as a critical component of radar systems. However, from the following statement made in 1946 by a Scientific American (National Materials Advisory Board 1994),

*High-frequency heating really started when engineers working on short-wave transmitters contracted artificial fevers. The great virtues of this kind of heat are as follows: The heat is generated directly in the object itself; no transfer of heat is involved. Associated apparatus need not be heated. The surfaces of the material need not be affected. The people who work with the equipment have cooler working conditions. No gases are involved and thus the likelihood of corroded surfaces is eliminated. The material can be heated from the inside-out. Finally, objects of unusual size or shape can be heated.*

it is obvious that the virtues of radio-frequency heating were forecasted earlier.

According to Gallawa’s website (2003), the microwave heating properties were first discovered in 1946 by Dr. Percy Spencer, a self-taught engineer with the Raytheon Corporation, when he discovered that during a radar-related research project the candy bar in his pocket had melted. By late 1946, the Raytheon Company had filed a patent proposing that microwaves to be used for cooking food and in 1952 it introduced the first microwave oven to the marketplace which became an omnipresent technology during the last two decades.
In time, the usefulness of microwave energy was found in other few industries as well. Besides microwave processing of food, the other commercial applications include: analytical chemistry, and heating and vulcanization of rubber.

Much work has been undertaken to investigate the use of microwaves for the processing of a wide range of materials, including ceramics, polymers, composites (ceramic and polymer matrix), powders, and minerals. Microwaves have also been investigated in a broad range of plasma processes (surface modification, chemical vapour infiltration, powder processing), chemical synthesis and processing, and waste remediation. However, there has been little industrial application to date, with most of the effort still in the laboratory stage.

Due to its characteristics, microwave processing may offer great opportunities and benefits to timber industry as well but so far, no much work has been done to become an industrial reality.

1.2 Theory Behind the Microwave Heating

A complex definition explains microwaves as being waves of energy associated with electric and magnetic fields (electromagnetic waves) having a free-space wavelength between 0.3 and 30 cm and corresponding to frequencies of 1–100 GHz (Academic Press Dictionary of Science Technology 1996; Hyperdictionary 2003).

Depending on practical applications, the waves can be used either to transmit information or just energy. In general, the second category of applications is called “microwave heating”. In this case the electromagnetic wave interacts directly with solid or liquid materials known as lossy dielectrics or lossy materials.

Any typical microwave heating system has three major components: the source (microwave generator), the transmission lines and the applicator. The microwave source generates the electromagnetic radiation which is generated from the acceleration of charge, and the transmission lines deliver the electromagnetic energy to the applicator where it is either absorbed or reflected by the material being processed. The theoretical analysis of each of these microwave components is governed by the Maxwell equations, which describe mathematically all phenomena of electromagnetism, and appropriate boundary conditions.
1.2.1 Maxwell’s equations and electromagnetic waves

In the second half of the nineteenth century, the Scottish physicist James Clerk Maxwell proposed that the equations of electricity (Ampere’s Law) needs one more term (the "displacement current"), representing an electric current which could travel through empty space, but only for very fast oscillations.

By putting together his findings and all previously established experimental facts regarding electric and magnetic fields, Maxwell formed four partial differential equations (generically named Maxwell’s equations), which provide the foundations of all electromagnetic phenomena and their applications. The Maxwell’s equations (Eq. 1-4) govern the principles of guiding and propagation of electromagnetic energy (Penick 2000).

\[
\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad \text{Faraday’s Law} \quad (1)
\]
\[
\nabla \cdot \mathbf{D} = \rho \quad \text{Gauss’ Law} \quad (2)
\]
\[
\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \quad \text{Ampere’s Law}\quad (3)
\]
\[
\nabla \cdot \mathbf{B} = 0 \quad \text{no name law} \quad (4)
\]

One of the first things that Maxwell did with his four equations was to look for wave-like solutions. Maxwell knew that the wave-like solutions of the equations of gas dynamics correspond to sound waves, and the wave-like solutions of the equations of fluid dynamics correspond to gravity waves in water. So, he reasoned that if his equations possessed wave-like solutions then these would correspond to a completely new type of wave, which he called an electromagnetic wave (Fitzpatrick 2004).

According to Maxwell’s theory, a propagating electromagnetic wave has two components: an electric field which is associated with voltage because it exerts a force on any electric charge placed on it, and a magnetic field which is associated with current because it tends to exert a force on any magnetic pole placed in it. The fields’ magnitude

---

2 Maxwell added the \( \frac{\partial \mathbf{D}}{\partial t} \) term to Ampere’s Law
varies periodically in both time and direction of propagation – Figure 1. The electric and magnetic field are vectors always perpendicular to each other and to the direction of wave propagation.

\[ \lambda = \frac{c}{f} \]

Figure 1: Propagation of a plane wave

The velocity \( c \) with which the wave propagates along the \( z \)-axis is given by the equation

\[ c = f\lambda \]

where \( \lambda \) represents the distance (wavelength) along the \( z \)-axis between successive wave crests and \( f \) is the oscillation frequency of the fields at a given point in space.

Maxwell established that the electromagnetic waves are able to propagate through vacuum and deduced that the speed of propagation of such wave through space is entirely determined by the constants \( \varepsilon_0 \) (permittivity of free space) and \( \mu_0 \) (permeability of free space) with well-known values at that time. Thus, when he calculated the velocity of electromagnetic waves he obtained:

\[ c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} = \frac{1}{\sqrt{8.85 \times 10^{-12} \left(4\pi \times 10^{-7}\right)}} = 2.998 \times 10^8 \quad \left[ \frac{m}{s} \right] \]
The excellent agreement between the obtained value of electromagnetic waves velocity through space and the velocity of light lead Maxwell to hypothesize that light is a form of electromagnetic wave.

To sum up, Maxwell proved that electric and magnetic fields travel through free space in the form of transversal electromagnetic waves at a constant velocity of $3 \times 10^8$ m/s. The validity of the self-propagating electromagnetic wave suggestion was later demonstrated in experiments by Heinrich Rudolf Hertz, and was fundamental to the invention of radio (Wikipedia 2004).

Without knowing about the existence of different types of electromagnetic waves other than visible light, Maxwell was able to predict at that time that visible light forms just a small element of a vast spectrum (Fitzpatrick 2004). Since Maxwell's time, virtually all of the non-visible parts of the electromagnetic spectrum (Figure 2) have been observed.

Figure 2: Electromagnetic spectrum and frequencies used in microwave processing (Sutton 1993)
Microwaves occupy the part of the electromagnetic spectrum from 300 MHz \( (3 \times 10^8 \text{ cycles/sec}) \) to 300 GHz \( (3 \times 10^{11} \text{ cycles/sec}) \). However, three main frequencies, 915 MHz, 2.45 GHz and 28 or 30 GHz, are freely allowed for microwave heating in industrial, scientific, and medical applications (ISM frequencies) but there may be deviations depending on the regulations in different countries. The lowest cost frequency is 2.45 GHz since the lower frequency of 915 MHz involves certain technical complications and is justified only in certain applications.

### 1.2.2 Volumetric and Selective Heating

In the last twenty years, the use of microwave energy has been seen an effective, reliable and adaptable source for selective volumetric heating of dielectric materials. Used in areas such as industrial, commercial, domestic and medical, with the sizes of these systems ranging from a few hundreds watts to over 250 kilowatts, microwave energy demonstrated that it is the new choice and a very versatile and powerful method for the heating of dielectric materials.

Microwaves of 2450 MHz operating frequency have been attracted the attention of researchers from various fields. The most distinguished characteristics of microwave from conventional heating are volumetric and selectivity.

It is known that microwaves can penetrate up to many meters in electrically insulating materials such as ceramics, polymers, and certain composite materials, and in other dielectric materials. However, the depth of penetration depends on several factors such as the wavelength of the radiation and the dielectric (and magnetic) properties of the material under microwave action. During the time that a material is exposed to penetrating microwave radiation, some of the energy is irreversibly lost (absorbed), which in turn generates heat within the volume (or bulk) of the material. This bulk heating raises the temperature of the materials such that the interior portions become hotter than the surface, because the surface loses heat to the cooler surroundings (due to low thermal conductivity of dielectric). This is the reverse of conventional heating, where heat from an external source is supplied to the exterior surface and diffuses toward the cooler interior regions. Thus, the reverse thermal gradients in microwave heating provide several unique benefits including rapid volumetric heating without
overheating the surface. This is observed, especially in materials with low thermal conductivity. Other benefits include reduced surface degradation during the drying of wet materials, and removal of binders or gases from the interior of porous materials without cracking or conversely, penetration of reactive gases (during chemical vapour infiltration) or fluids into the hotter interior portions of porous materials (National Materials Advisory Board 1994).

In order to better understand the factors involved in microwave heating, the following equations detail the major variables involved in microwave absorption.

The average energy per unit volume of dielectric converted into heat is expressed by:

\[ P_{\text{abs.}} = \omega \epsilon_0 \epsilon'^* E^2 \quad [\text{W/m}^3] \quad (7) \]

where \( \omega \) is angular frequency, \( \epsilon_0 \) is permittivity of free space and \( \epsilon'^* \) is dielectric loss factor.

Depending on the dielectric properties of material, its geometry and the applicator configuration, the electric field strength within dielectric decays exponentially as \( E e^{-az} \) (Figure 3).

Figure 3: Exponential decay of the electric field in a lossy dielectric (Datta and Anantheswaran 2001)
Thus, the energy at a point distance $z$ away from the surface of the material is given by:

$$P_z = P_{out}e^{-2\alpha z}$$

(8)

where $P_{out}$ is the output power from the source and $\alpha$ is the attenuation constant with the following expression:

$$\alpha = \frac{2\pi}{\lambda_0} \sqrt{\frac{\varepsilon'}{2\varepsilon''}} \left[ \sqrt{1 + \tan^2 \delta} \right] - 1 \quad [\text{Np/m}]$$

(9)

where $\lambda_0$ is the wavelength in free space, $\varepsilon'$ is the dielectric constant of the dielectric medium and $\tan \delta$ is the loss tangent.

Besides the material properties such as thermal and heat conductivity, the penetration depth is one of the factors which determines the heat distribution within material. The penetration depth, $D_p$ is defined as the depth into the material at which the power density reduces to $1/e (= 0.368)$ of its surface value (Metaxas and Meredith 1993).

$$D_p = \frac{1}{2\alpha}$$

$$= \frac{\lambda_0}{2\pi \sqrt{2\varepsilon'}} \sqrt{\frac{1}{1 + \left( \frac{\varepsilon''}{\varepsilon'} \right)^2}} - 1 \quad [\text{m}]$$

(10)

$D_p$ does not mean that there is no heating at a depth exceeding the penetration depth. The heat dissipated in the layer bounded by the surface and the plane at depth $D_p$ is 63.2% of the total. The remaining percentage is dissipated in the material at depths greater than $D_p$ (Meredith 1998).
1.3 Microwave Heating Process of Wood

The use of microwave processing techniques in wood production is still a novel and revolutionary concept. High intensity microwave treatment creates changes in wood structure, which might significantly contribute to the development needs of timber industry, by accelerating wood drying time, relieving of growth stresses, facilitating preservative impregnation and enabling the production of solid wood products (Figure 4).

![Microwave processing could offer a powerful material-processing tool to wood industry](image)

Figure 4: The potential of microwave applications in wood industry (Daian 2005)

When an electric field interacts with a material, various responses may take place. The main effect of the microwave-material interaction is the conversion of microwave energy into heat within the material. This physical phenomenon is the result of the electromagnetic energy absorption caused by the dielectric properties of the material.
1.3.1 Dielectric response of wood

The wood ability to absorb and store electrical potential energy is measured by the wood permittivity, otherwise known as the dielectric parameters of wood. The equation for complex permittivity is:

\[ \varepsilon^* = \varepsilon' - i\varepsilon'' \quad (11) \]

\[ \tan\delta = \frac{\varepsilon''}{\varepsilon'} \quad (12) \]

The real component of the permittivity, known also as the dielectric constant (\(\varepsilon'\)), characterises the penetration of microwave in a material (the material ability to store energy). The imaginary component, the dielectric loss factor (\(\varepsilon''\)), indicates the material’s ability to accumulate the energy. A substance is lossless if \(\varepsilon'' = 0\). The quantity embodied by \(\tan\delta\) is named loss tangent and indicates the ability of wood to convert absorbed energy into heat. It is the most important parameter in microwave processing.

The dielectric response of wood at electromagnetic energy results from polarisation mechanism. It is generally assumed that within the perfectly conducting materials, under an electric field, either free motion of the electrons or collective diffusion of charge occurs. For dielectrics, the situation is quite different since instead of the motion of electrons or ions three processes may take place: space charges due to electronic conduction, atomic (ionic) polarisation associated with far-infrared vibrations and rotation or orientation of electric dipoles (Newnham et al. 1991). If the dielectric is non-homogenous, the forth polarisation process caused by the charges which build up at interfaces may occur. Overall, the mechanism is called polarisation and generates the microwave absorption (Kittel 1959; Debye 1929).

The electronic and ionic conduction do not contribute to microwave heating of wood and they can be neglected. In that case it follows that at microwave frequencies the dipole polarisation contributes to both \(\varepsilon'\) and \(\varepsilon''\).

have performed scientific work on dielectric properties of wood. The literature comprises data on the dielectric properties of wood with different moisture contents, densities, temperatures, and at different frequencies with the electric field strength vector, $\vec{E}$, acting in the three wood structural directions. This research demonstrates that the dielectric properties of wood vary widely with physical parameters such as moisture content, density, grain direction, frequency and temperature.

### 1.3.2 Physical model of microwave heating of wood

Under electromagnetic radiation, dielectrics heat more effectively than insulating and highly conductive materials. Although the microwave penetration is significant within low-loss insulators, they are difficult to heat above the room temperature. In contrast, the electromagnetic waves cannot propagate very far through a highly-conducting medium. They are considerably attenuated and largely reflected due to the skin effect. When a large current flows inside the sample, due to a high conductivity, a combination of the magnetic field with the current produces a force which pushes conducting electrons outward into a narrow area adjacent to the boundary (National Materials Advisory Board 1994).

In general, the industrial microwave process involves many complicated physical phenomena. It includes absorption of the electromagnetic energy, transport of the generated heat, shape and dimension changes of the wood, phase changes in the water, transport of the water through the wood material, etc.

The most important factor in the processing of wood by microwaves is the complex dielectric permittivity of the wood that determines the distribution of the electromagnetic fields and the absorption of the supplied energy. The generation of heat in wood using microwave energy establishes a temperature distribution in the material changing its moisture and density. Heat losses, heat diffusion and specific heat changes will modify the temperature field (Tinga 1993) and therefore the wood internal pressure. Overall, the heating process results in a complex change in the dielectric properties of wood. The non-linear change of the dielectric properties of wood in the heating process is represented in Figure 5.
As shown in Figure 5, the inherent feedback paths depicting complex multiple factors influencing microwave heating process provide input to the algorithm used in the determination of dielectric permittivity of green wood at a given stage.

1.3.3 Microwave drying of wood - the response to its physical characteristics

Wood possesses specific structural and physical properties which can explain its microwave drying stages.

Heterogenous and anisotropic

Structurally, wood is composed of bark, sapwood, heartwood, and pith. Each wood cell has a cavity (lumen) and walls composed of several layers arranged in different ways. Most of the tubelike cells are oriented parallel to the long axis of the tree and are termed fibers, tracheids, or vessels, depending on their particular anatomical

---

3 Sapwood is the light-outer area of wood in the trunk and branches made of living cells which upwardly conduct the raw sap and store substances. Heartwood is the inner area of wood which no longer contains living cells and is more dense and durable but less permeable and flexible than sapwood. The pith is the axial part of the stem with low density and surrounded by the first growth ring.
characteristics and function. Another type of cell, the wood ray, lies on radial lines from
the center of the tree outward and perpendicular to the length of the tree (Forest
Products Laboratory 1991).

The moist wood is composed of substances in solid, liquid and gaseous phases. The
solid phase consists of the wood cell walls whose constituents are cellulose,
hemicelluloses and lignin. The cell walls absorb moisture, forming bound water. The
cell walls, the interfibril channels and lumens are partially filled with air and vapour. If
the quantity of moisture exceeds the fiber saturation point (FSP)\(^4\), the cell cavities
become filled with water (Torgovnikov 1993).

To summarize, emerging from its special anatomic structure, wood is a
complex material with non-homogenous and non-isotropic properties.

Due to the anisotropy, the physical properties of wood such as: density, thermal
and electrical properties are distinguished and different in the three directions which are
generally adopted for examinations of wood structure (Figure 6).

![Figure 6: Principal directions on wood stem (Keam Holden Associates Ltd. 1999)](image)

**Poor thermal and moderate electrical conductor**

Wood is a poor thermal conductor. Heat is not rapidly transported into the
surroundings when some region becomes hot. The thermal conductivity of common
structural woods is about two to four times greater than that of common insulating
material and more than two thousand times less than that of highly thermal conducting
materials.

\(^4\) The fiber saturation point is the moisture content at which the cell wall is saturated with bound water but
no free water is present.
From the electrical point of view, completely dried wood is an insulator. Its resistivity is about $10^{14}$ to $10^{16} \, \Omega \text{m}$. Due to the moisture, wet wood become a dielectric with a resistivity of $10^3 \div 10^4 \, \Omega \text{m}$ at fiber saturation (Forest Products Laboratory 1999).

In addition to moisture content which greatly influences both electrical and thermal conductivities, there are a couple of other basic factors (e.g. density, extractive content, grain direction, structural irregularities such as checks and knots, fibril angle, and temperature) which may affect them.

**Non-permeable under microwave energy**

Due to the microwave-heating characteristic to heat from interior to exterior (surface temperature stays colder during the initial periods of heating), in microwave processing wood become a not very permeable material (no passageways for water to get out). Hence, the internal pressure increases according to the saturated pressure of water vs. temperature. Being a dielectric, the response of wood at electromagnetic energy results from polarisation mechanism.

Due to the structural and physical properties of wood and the microwave-heating characteristic to heat from the interior to exterior during the microwave heating process, the internal wood temperatures can reach values that are significantly above the boiling point of water at room conditions. Also, the internal pressure varies according to the saturated pressure of water vapour vs. temperature. As illustrated in Figure 7, four distinct drying periods of wood are identified: heating, streaming, enthalpic period and thermal runaway.
In period 1, which is known as the *heating period*, the energy is transferred directly from the microwave field to the wood and very little mass loss is incurred.

During period 2, known as the *streaming period*, the temperature increases and passes through the boiling point of water. The resultant large internal vapor pressure drives the liquid from the medium quickly and efficiently under the action of pumping phenomenon.

During period 3, which is known as the *enthalpic period*, the moisture content promptly decreases and under the influence of the elevated internal temperatures, vapor transport becomes the dominant migration mechanism because of the sustained vaporization that exists within the medium.

The final period, known as the *period of thermal runaway*, commences when the medium becomes dry in certain locations and the temperature increases rapidly due to the characteristics of the dielectric loss factor. During this period, hot-spots and consequently, burning can become evident and the material can be severely damaged (Perre and Turner 1999).

---

**Figure 7:** Microwave drying periods for wood (Daian 2005)
Since the discovery of the industry benefits from the use of electromagnetic energy, a considerable investment has been made in the development of microwave processing systems for a wide range of products including food, rubber, ceramics, wood and other dielectric materials. At the beginning, the microwave technology was tried and developed by small, industrial microwave companies working with users in joint development arrangements or other combinations. As a result, much of the technology that has been developed to date is not widely available, so any further development or any other possible application of microwave power has to involve new modelling, tests, and design for equipment and processes which finally will offer others the potential benefits of microwave processing.

Generally speaking, the basic components of a microwave processing system (i.e. generator, applicator, control systems and leakage suppressor) are simple. The complicated part arises from the need to model and develop the interaction of materials with microwave fields and to observe the changes in fundamental material properties during processing. All these make design and development of microwave processes very complex.

Below, some general aspects of the microwave systems component are presented.

2.1 Microwave Generators

The microwave source or generator is “the heart” of any microwave system. It generates the electromagnetic radiation from the acceleration of electric charge.
Major advances in microwave generation and generators occurred in the early 1940s with the invention, rapid development and deployment of the cavity magnetron on the heels of the earlier (1938) invention of the Klystron - Figure 8.

Figure 8: Microwave tube development (National Materials Advisory Board 1994)

The performances and limitations of the various microwave generators (i.e. magnetrons, klystrons, travelling wave tubes) over the time is shown in the following device performance range on a power-frequency plot - Figure 9.
Factors with big influence on the microwave specific applications are not only the power and frequency but also other performance factors. These are recognized to be gain, linearity, noise, phase and amplitude stability, coherence, size, weight, and cost must also be considered (National Materials Advisory Board 1994).

The most widely used electromagnetic generator is magnetron, which over years of development of microwave generators, together with its usage in more and more application as the “workhorse”, became the economic product of choice for the generation of electromagnetic power. Basically the magnetrons are the tubes used in conventional microwave ovens found currently in almost every home in developed countries. Magnetrons have power on the order of a kilowatt (1000 watts) in the 2-3 GHz range (2.45 GHz) and in industrial ovens with output up to a megawatt ($10^6$ watts).

Because around the world civil and military radars are employing tens of thousands of magnetrons and household ovens employing the so-called "cooker magnetron" number in the tens of millions. This large quantities lead to lower cost, and
thus for many microwave heating and processing applications, the magnetron is the device of choice, with great advantages in size, weight, efficiency, and operational costs.

The magnetron is the major player in class of generators termed "crossed field", so named because the basic interaction depends upon electron motion in electric and magnetic fields that are perpendicular to one another and thus "crossed" (National Materials Advisory Board 1994).

In its most familiar structure, shown schematically in Figure 10, a cylindrical electron emitter, or cathode, is surrounded by a cylindrical structure, or anode, at high potential and capable of supporting microwave fields. Magnets are arranged to supply a magnetic field parallel to the axis and hence perpendicular to the anode cathode electric field.

![Figure 10: Schematic diagram of a magnetron shown in cross-section (National Materials Advisory Board 1994)](image)

The interaction of electrons travelling in this crossed field and microwave fields supplied by the anode causes a net energy transfer from the applied DC voltage to the microwave field. The interaction occurs continuously as the electrons traverse the cathode anode region. The magnetron is the most efficient of the microwave generators achieving efficiencies of 90 percent, while the common efficiency is 70-80 percent.
(National Materials Advisory Board 1994). Figure 11 and Figure 12 show the "conventional magnetron".

Figure 11: Cross-section of a magnetron (Gallawa 1997)

Figure 12: 2.45 GHz magnetron (Naudin 2005)
2.2 Transmission Lines

As a general definition, “transmission line” is a device that transfers energy from one point to another with a minimum loss (Laverghetta 1988). In other words, microwave transmission lines couple the energy of the microwave source to the applicator. Different types of transmission lines can be distinguished: waveguides, coaxial cables.

To define the certain properties, which are common to all types of transmission lines, the two-wire transmission line with the four components: capacitance (C), inductance (L), resistance (R) and conductance (G), is considered - Figure 13.

![Figure 13: Equivalent circuit of a transmission line (Laverghetta, 1988)](image)

The voltage generated within the line is a voltage wave and the current induced is a current wave. The resulting flux linkages per unit of current, set up by these waves, accounts for the inductance (L). The shunt capacitance (C) is a result of a charge on the conductor being proportional to the potential difference, or voltage, on the line. The conductive element (G) results, if the dielectric medium between the conductors is not perfect. The resistance (R) depends on the resistivity of the material used, the length and cross section of the conductor and the distribution of currents in the cross section. In most microwave transmission lines the losses are extremely small; therefore the parameters R and G are kept nearly zero (Laverghetta 1984).

Microwave field within a transmission line can be divided into three types: transverse electromagnetic (TEM), transverse electric (TE) and transverse magnetic (TM) waves - Figure 14.
Waveguide: A waveguide is a pipe or conduit with different cross section for propagating and channelling electromagnetic energy - Figure 15. In the microwave frequency range, conducting pipes have either a rectangular or a circular cross section.
At higher frequencies, power transmission can be thought of in term of travelling electromagnetic waves. In waveguides, the waves are transverse electric (TE) and transverse magnetic (TM) and always are propagated in $z$ direction. The TE wave has the field components $E_x, E_y, H_y, H_z$, and $H_z$ (the $z$ component of the electric field, $E_z$, is missing) whereas the TM wave has $E_x, E_y, E_z, H_y$, and $H_x$ field components (the $z$ component of the magnetic field, $H_z$, is missing). For the cylindrical waveguides, the TE wave has the field components $E_r, E_{\phi}, H_r, H_{\phi}$, and $H_z$ and the TM wave $E_r, E_{\phi}, E_z, H_r$, and $H_{\phi}$.

Each TE and TM wave in a waveguide can have different field configurations. Figure 16 and Figure 17 show the field distributions of some lower-order waveguide modes. In figures, electric fields are represented by solid lines and magnetic fields by dashed lines. Each field configuration is called a mode and is identified by the indexes $m$, $n$, and $l$. TE$_{mn}$ and TM$_{mn}$ modes are considered in rectangular waveguides and TE$_{nl}$ and TM$_{nl}$ modes are considered in cylindrical waveguides. The subscripts denote the number of half-wavelength in the $x$, $y$ and $r$, $\phi$ directions, respectively. They can be any integer: 0, 1, 2, etc.

In commercial installations, the rectangular waveguide is the most frequently used to carry the energy from the power source to applicator. Commercial waveguides are available in diverse sizes with specified operating frequency range for each. Assuming that TE$_{10}$ is the designed mode for frequency 2.45 GHz, standard waveguide is WR 384 with inner dimensions 0.046 m by 0.086 m. The larger dimension is referred to as the “width” while the term “height” is applied to the smaller dimension.
Figure 16: Field distributions and key expressions of calculation for modes in rectangular waveguides (NMAB 1994)
Figure 17: Field distributions and key expressions of calculation for modes in cylindrical waveguides (NMAB 1994)
The wavelength, $\lambda_g$, and the wave impedances, $Z_{TE}$ and $Z_{TM}$, for the TE and TM waves, respectively, can be expressed in terms of $k_i$ and $k_c$, such as:

$$\lambda_g = \frac{2\pi}{\sqrt{(k_i^2 - k_c^2)}}$$  \hspace{1cm} (13)

$$Z_{TM} = \frac{(2\pi / \lambda_g)}{\omega \varepsilon_0 \varepsilon'_{\prime}}$$  \hspace{1cm} (14)

$$Z_{TE} = \frac{\omega \mu_0 \mu'_{\prime}}{(2\pi / \lambda_g)}$$  \hspace{1cm} (15)

The Eq. 13, 14 and 15 are true for all waveguides. Consider first the calculation of the wavelength in Eq. 13. The wavelength must be real and positive by definition. That is true only when $k_c$ is smaller than $k_i$. The waveguide mode indices, $m$ and $n$, can be any integer including zero, but both cannot be zero. Since $k_c$ involves $m$ and $n$, only a limited number of combinations of the values of $m$ and $n$ can keep $k_c$ smaller than $k_i$. The number of the modes that can propagate in a waveguide is therefore limited. For small values of "a" and "b" such that the condition $k_c < k_i$ cannot be met, no waveguide mode can exist, and the waveguide is at cutoff frequency. For some specific values of "a" and "b," only one mode satisfies the condition $k_c < k_i$, and the waveguide is called a single-mode waveguide. For very large values of "a" and "b," thousands of the modes satisfy the condition, and the waveguide is a multimode waveguide.

**Coaxial cable**: A coaxial cable is a transmission line, technically consisting of two circular conductors being separated by a continuous solid dielectric or by dielectric spacers such as polyethylene or Teflon (Figure 18). A wide variety of materials are used as centre conductors of coaxial cables. Usually, the material is copper often covered with a high conductance material such as silver. The second conductor is the one that completely surrounds the first conductor and it is either a woven braid in flexible cable or a solid tube structure in semi-rigid cable.
For any particular applications, an investigation of some parameters that must be considered is needed to make the cable choices accordingly. The first important cable parameter is characteristic impedance\(^5\). It is the value of resistance, present all along the cable. Most microwave systems use a characteristic impedance of 70 or 50 ohms. The second most important cable parameter is the attenuation of the cable used for the application. The attenuation in a coaxial cable depends on its physical construction, the frequency of operation (Laverghetta 1984) and dielectric insertion (if it is used).

In coaxial line, the waves are transverse electromagnetic–TEM. For the TEM wave, the electric field has only a radial component, \(E_\rho\), and the magnetic field only an azimuthal component, \(H_\phi\) (all fields are transverse) - Figure 19. It is an approximation of the radiation wave in free space. Also it is the wave that propagates between two parallel wires and two parallel plates.

\(^5\) The ratio of voltage to current at every point along the line
2.2.1 Reflection and transmission parameters

The quantities, which characterise the microwave networks, are related to scattering or S-parameters. The number of S-parameters for a given device is equal to the square of the number of ports. If the device under test (DUT) is regarded as two-port network, it has four S-parameters (Figure 20).

\[
\begin{bmatrix}
S_{11} & S_{12} \\
S_{21} & S_{22}
\end{bmatrix}
\]

Figure 20: Definition of the two-port network (Agilent Technologies 2004)

The S-parameters for a two-port network are defined using the reflected or emanating waves, \(b_1\) and \(b_2\), as the dependent variables, and the incident waves, \(a_1\) and \(a_2\), as the independent variables. The general equations for these waves as a function of the S-parameters are:

\[
\begin{align*}
    b_1 &= S_{11}a_1 + S_{12}a_2 \\
    b_2 &= S_{21}a_1 + S_{22}a_2
\end{align*}
\]  \hspace{1cm} (16)

The numbering convention of S-parameters is that the first number following \(S\) is the port at which energy emerges and the second number is the port at which energy enters. Therefore, \(S_{11}, S_{22}\) indicates a reflection measurement (reflection coefficients) and \(S_{12}, S_{21}\), have the meaning of transmission coefficients (Figure 21).
Using the scattering equations, Eq. 16, the individual S-parameters can be determined by taking the ratio of the reflected or transmitted wave to the incident wave with a perfect termination placed at the output (Figure 22).

The reflection/transmission parameters can also be expressed in other familiar forms - Figure 23.

Figure 21: S-parameters (Agilent Technologies 2000)

Figure 22: Measuring S-parameters (Agilent Technologies 2000)
The vector and scalar expressions of the reflection waves are presented in Figure 24.

Reflection coefficient: \[ \Gamma = \frac{E_{\text{refl}}}{E_{\text{inc}}} = \rho e^{i\phi} = \frac{Z_L - Z_0}{Z_L + Z_0} \]

Power loss: \[ RL(dB) = -20 \log\left(\frac{E_{\text{refl}}}{E_{\text{inc}}}\right) = -20 \log(\rho) \]

Voltage Standing Wave Ratio: \[ VSWR = \frac{E_{\text{max}}}{E_{\text{min}}} = \frac{1 + \rho}{1 - \rho} \]

<table>
<thead>
<tr>
<th>No reflection ((Z_L = Z_0))</th>
<th>Full reflection ((Z_L) - open, short)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 dB</td>
<td>1</td>
</tr>
<tr>
<td>(1)</td>
<td>(0) dB</td>
</tr>
<tr>
<td>(\infty) dB</td>
<td>(\infty) VSWR</td>
</tr>
</tbody>
</table>

In the same manner, the most common transmission parameters are described in Figure 25. In addition to these, group delay is another useful parameter in communication systems. It is a measure of the transit time of a signal through a DUT.
versus frequency. Group delay can be calculated by differentiating the DUT’s phase response versus frequency.

Transmission coefficient: $T = \frac{E_{\text{trans}}}{E_{\text{inc}}} = e^{j\phi}$

Insertion loss/attenuation (dB) = $-20 \log \left| \frac{E_{\text{trans}}}{E_{\text{inc}}} \right| = -20 \log \tau$

Figure 25: Transmission parameters (Agilent Technologies 2000)

### 2.2.2 Fresnel reflection and transmission coefficients

The Fresnel equation gives the ratio of the reflected and transmitted electric field amplitude to initial electric field for electromagnetic radiation incident on a dielectric - Figure 26. The coefficients for reflection and transmission of the electric field parallel to the plane of incidence - “transverse electric field” (abbreviated TE) are denoted $r_\perp$ and $t_\perp$ respectively.

Figure 26: Reflected and transmitted electric field diagram (ScienceWorld 2006)
The coefficients give the amount of the electromagnetic wave reflected from a dielectric and transmitted through a dielectric for TE radiation:

\[
\begin{align*}
    r_\perp &= \frac{E_\perp}{E_i} = \frac{n_1 \cos \theta_i - n_2 \cos \theta_r}{n_1 \cos \theta_i + n_2 \cos \theta_r} \\
    t_\perp &= \frac{E_\perp}{E_i} = \frac{2 n_1 \cos \theta_i}{n_1 \cos \theta_i + n_2 \cos \theta_r}
\end{align*}
\]

(17) (18)

where \( n_1 \) and \( n_2 \) are the index of refraction of the original and dielectric medium. The index of refraction is given in terms of the electric permittivity \( \varepsilon \) and magnetic permeability \( \mu \) by:

\[ n = \sqrt{\varepsilon \times \mu} \]

(19)

As the permeability of medium is very nearly to that of vacuum, i.e. \( \mu = 1 \), the index of refraction is given by:

\[ n = \sqrt{\frac{\varepsilon}{\varepsilon_0}} \]

(20)

In addition to the amplitude coefficients, power (or intensity) coefficients are often defined as the square of the corresponding amplitude coefficients, i.e.

\[
\begin{align*}
    R_\perp &= |r_\perp|^2 \\
    T_\perp &= |t_\perp|^2
\end{align*}
\]

(21) (22)

For normal incidence \( \theta = \theta' = 0 \).
\[ r_\perp = \frac{E_r}{E_i} = \frac{n_1 - n_2}{n_1 + n_2} \]  

(23)

\[ t_\perp = \frac{E_t}{E_i} = \frac{2n_1}{n_1 + n_2} \]  

(24)

and

\[ R_\perp = \left( \frac{n_1 - n_2}{n_1 + n_2} \right)^2 \]  

(25)

\[ T_\perp = \left( \frac{2n_1}{n_1 + n_2} \right)^2 \]  

(26)

If first medium is air, the equations transform to the simplest form:

\[ R_\perp = \left( \frac{n_1 - 1}{n_1 + n_2} \right)^2 = \left( \frac{\sqrt{\varepsilon} - 1}{\sqrt{\varepsilon} + 1} \right)^2 \]  

(27)

\[ T_\perp = \left( \frac{2}{n_1 + 1} \right)^2 = \left( \frac{2}{\sqrt{\varepsilon} + 1} \right)^2 \]  

(28)

Using Snell’s law

\[ n_1 \times \sin \theta = n_2 \times \sin \theta ' \]  

(29)

gives
\[ R_\perp = \left( \frac{1}{\varepsilon} \cos \theta - \sqrt{1 - \frac{1}{\varepsilon}} \sin^2 \theta \right) \left( \frac{1}{\varepsilon} \cos \theta + \sqrt{1 - \frac{1}{\varepsilon}} \sin^2 \theta \right) \]  

(30)

\[ T_\perp = \left( \frac{2}{\varepsilon} \cos \theta \right)^2 \left( \frac{1}{\varepsilon} \cos \theta + \sqrt{1 - \frac{1}{\varepsilon}} \sin^2 \theta \right) \]  

(31)

Note: there is a “magic” angle for which \(|\Gamma| \approx 0\).

### 2.3 Microwave Applicators

The microwave part, which is used to apply the electromagnetic energy to the dielectric material, is microwave applicator. These devices need special consideration because their design needs to match with the proposed application.

Note: text and figures omitted - copyrighted material

From electromagnetic point of view, there are general classes of microwave applicators: multimode and single mode cavities.

#### 2.3.1 Single-mode applicators
The single-mode applicators, consist in their simplest form of a section of waveguide operating near cutoff frequency (1.7 GHz) for the applicators operating at 2.45 Ghz. This kind of applicators usually has holes or slots cut in them to let product get in or out.

Note: text and figures omitted - copyrighted material

Figure 27 illustrates two examples of single-mode applicators. The first is a single-mode waveguide with a slot cut into the broad wall to permit passage of a thin material that is to be heated. Cutting the slot in the centre of the broad wall of the cavity where the TE$_{10}$ electric field is at a maximum ensures efficient coupling. The second is a cylindrical cavity operating in the TM$_{01}$ mode which have the E-fields parallel to the longitudinal axis of the cylinder.
a) Single-mode waveguide

b) Cylindrical single-mode cavity

Figure 27: Single-mode applicators (NMAB 1994)
2.3.2 Multimode applicators

For the microwave industrial application suitable to our times the multimode ovens are the most accepted due to the following key features and benefits:

Note: text and figures omitted - copyrighted material

Microwave computer modelling and small-scale industrial experiments showed that when the dimensions of the applicators are very large when expressed in terms of the free-space wavelength of the operating frequency, a large number of standing-wave modes can exist at or very near the operating frequency inside the cavity. It is desirable to excite as many of these modes as possible in order to establish reasonable uniform electric field strength all around the cavity. Moreover, the heating non-uniformity is minimized even when the field perturbing effects of the materials being processed are present when multiple modes are excited.

The computer modelling and design of the multimode applicator involves a number of basic design parameters such as: uniformity of heating, required microwave power, applicator size, leakage suppression and also the required performance characteristics.

2.4 Microwave Systems’ Design Parameters

The equipment used for industrial microwave processing is generally custom-designed and optimised based on specific application needs. Operating characteristics
are determined in case-by-case application and function of the dielectric material, which has to be processed and function of the desired output.

Starting from the design, it is needed to know the basic parameters which determine the required power and type of applicator. Then, moisture contents, dielectric properties, shape and size of the product and any special handling requirements are also important to be established. Not only the modelling but also pilot plant drying tests can relatively quickly determine whether or not the technique is technically feasible, especially with regard to possible power absorption and internal mass transfer effects, without requiring detailed knowledge of the properties of the material.

There are several key factors that should be considered in the design of any industrial microwave heating system. The most important ones are: heating uniformity, customized microwave power, applicator size and microwave suppressor.

2.4.1 Heating uniformity

Note: text and figures omitted - copyrighted material
2.4.2 Required microwave power

Another important factor not only from application purpose point of view but also from economical benefits side is the required power.

This is usually calculated based on an initial assessment of the proposed process. Once an initial oven concept, layout and size have been established, it is further verified through actual testing. Key parameters to be verified include heating-rate sensitivity, temperature uniformity and process efficiency. A problem in some drying applications, i.e. rate sensitivity, may force the use of a longer cavity to increase process time but at the expense of process efficiency.

In order to control the equipment and to try to avoid abnormal behaviour, the power control can be achieved by the altering the current for the magnetic field or the anode current of the magnetron. This process can be achieved by building a sensors control system. As well the inclusion of the safety measures for the equipment will include interlocks on cooling, arc detectors in the magnetron mounting guides and anode temperature sensors.

2.4.3 Applicator size

Basically, in many applications, applicator size is determined largely by the product size and compatibility with existing factory conveyor or batch production formats. The determination of the minimum size for an oven is done considering the product size, mode number (uniformity requirement) and microwave-power handling capability under no-load conditions.
Many batch ovens are designed to process a fast travelling load which means that at the end of the process the cavity is effectively empty. In this case the cavity has to be in such way designed that the microwave leakage has to be in standardized limits.

The modelling and design process for applicator must prepare the possibility to allow no-load operation or to provide devices able to detect and automatically shut down the microwave energy from the magnetron when safe operating conditions are exceeded.

### 2.4.4 Microwave suppressors

Nowadays, the operators’ safety represents the main point besides the microwave equipment productivity and performances. The suppression of microwave leakage from microwave oven doors and product openings has to be strictly monitored. Also, reducing electromagnetic interference is required. Although these are two very different issues, they must be dealt with simultaneously by designing chokes or suppression tunnels. The current safety standard for microwave ovens is a radiation specification that limits emissions at a distance of 5 cm from the surface of an oven to a maximum of 5 mW/cm².

Leakage can usually be suppressed by means of reactive chokes, provided that the other dimension of the opening is less than approximately one-half of a wavelength. Good examples of these types of openings are the door seals for industrial and conventional home microwave ovens and slot openings of thin belt web materials processed in industrial microwave ovens.

Reactive chokes are ineffective when the height of the opening is greater than about half a wavelength. In these cases, free radiation from the cavity can occur with the
possibility of unacceptable levels of human exposure. There are three basic methods employed to deal with these situations. They are: leakage suppression tunnels with absorbent walls; vestibules with indexing conveyors and doors that open and close sequentially to admit product; and "maze" openings that admit product by causing it to meander through a folded corridor lined with absorbing walls (NMAB 1994). These are illustrated schematically in Figure 28.

More details about the leakage suppression devices are presented in Chapter 2.6.
Figure 28: Schematic of leakage suppression approaches (NMAB 1994)
2.5 Operational Health and Safety Measures – Microwave Safety Standards

Currently in the world, since the expansion of the microwave industrial application and the usage of more powerful microwave generators, potential hazards associated with exposure to radiation become more important. In many applications, open-ended waveguide systems are usually employed because microwaves must interact dynamically with the material to be processed. A major concern in such systems is the hazardous effect of microwave energy leakage on human tissues.

Many studies indicate that the effects of microwaves on biological tissue are thermal in nature. The only effect of radiation in the microwave region on human tissue is presently warming of the human tissue from the conversion of electromagnetic energy to heat. Thus, microwave exposure standards are based on the thermal effects of exposure.

The lens of the eye is particularly sensitive to intense heat, and exposure to high levels of microwaves can cause cataracts. Likewise, the testes are very sensitive to changes in temperature. Accidental exposure to high levels of microwave energy can produce temporary sterility.

More, it was determined that the absorption of RF/MW energy varies with frequency. Microwave radiation is absorbed near the skin, whereas RF radiation may be absorbed in deep body organs.

In order to minimize exposure, the microwave system needs to be designed with effective microwave leakage suppression devices (Figure 29) and/or an interlock system on doors and access apertures to shut off power when doors are opened.
By knowing these possible hazards, safety issues must be seriously considered in the practical implementation of microwave industrial systems with open ports. To preserve the radiation of these open-ended waveguide systems into permissible levels, bandstop microwave filters, water traps, dummy loads and other choke systems are widely used.

Conveyorized microwave ovens have been used in industry for many years to cook or thaw foods and provide heat for processing objects such as rubber and foundry cores. These ovens generally operate at 915 MHz or 2450 MHz because these frequencies are within the frequency bands designated by government agencies for such purpose. The intensity of microwave energy permitted to leak from domestic and/or industrial microwave heating systems is restricted.

Generally, the required design of oven doors should restrict this leakage to a level well below that recommended by the Australian/New Zealand Standard AS/NZS3350.2.25: 1997.
The Standard states, “The microwave leakage at any point 50 millimetres or more from the external surface of the appliance shall not exceed 50 watts per square metre”. This Standard applies to ovens designed for domestic applications, even if used in a workplace. The recommended limit is conservative and includes significant safety factors, so that even leakage levels marginally above the limit will have no effect on human health - Figure 30.

This standard limits the amount of microwaves that can leak from an oven throughout its lifetime. This is far below the level known to harm people. Furthermore, as you move away from a microwave power source, the level of any leaking microwave radiation that might be reaching you decreases dramatically.

![Australian Standard AS2772.1–1990](image)


Figure 30: Australian standard AS2772.1-1990 radio frequency radiation (Standards Association of Australia 1991)

On the world the International Microwave Power Institute has adopted a standard for intensity of microwave energy radiation leakage, which states that the MW radiation has to be "less than ten milliwatts per square centimetres".
Generally microwave industrial equipment is built to have no more than this leakage at the openings of the ports. By having this in place it should be clear that that for practical distances from the microwave equipment, for the operator, the levels should be much less due to the fact that the power level decreases inversely with the square of the distance. It is required for the user that the leakage level to be checked at the change of every work shift and to be sure that there are not any significant changes in leakage levels. As a double safety measures all panels and entrances are interlocked with the supply to prevent operation in the case they should be opened.

2.6 Suppressors/Choke Systems & Other Materials and Devices Related to Microwave Leakage Suppression and Microwave Leakage Prevention

In the case of a flow oven, the applicator is always in the form of a tunnel with an aperture at each end. At each end of the tunnel there is a structure known as a choke tunnel. The choke tunnel is designed to attenuate the microwave energy so that only safe levels exist at the tunnel mouth.

It is known that the International and National Safety Standards limits and regulate the use of electromagnetic energy and by that are set the design parameters for choke tunnel performance. By improving the choke tunnel attenuation, the total radiated power is reduced providing that there is no leakage elsewhere.

Historically there are three principles which designers of choke tunnels have used, these are: reactive choking, resistive absorption by the workload and resistive absorption in the choke tunnel.

Reactive choking involves creating a high reflection coefficient to energy escaping through the tunnel, using passive lossless reflectors. These normally take the form of an array of resonant slots or posts forming a bandstop filter. The simplest design which has an analytical solution is shown in Figure 31.
The attenuation per section of such a structure is given by the equation:

$$\alpha = 8.686 \cosh \left( \cos \left( \frac{2\pi d}{\lambda_g} \right) - \frac{b}{2h} \left( \tan \left( \frac{2\pi d}{\lambda_g} \right) \right) \sin \left( \frac{2\pi d}{\lambda_g} \right) \right)$$  \hspace{1cm} (32)$$

The slot depth becomes progressively more critical as the headroom height \( h \) increases. For \( b = l / 4 \) and \( h = 2b \) there is a theoretical attenuation of 15dB per section with a working height of 165mm. A four-section filter as described above would have a theoretical attenuation of 60dB. The corrugations can be broken up into square posts so that effectively two orthogonal filters are formed. The mechanical design is then further simplified by replacing the square posts with round ones.

The basic principle of resistive absorption is to use the complex part of the permittivity of a dielectric to cause resistive loss and hence heating up of the dielectric. If the workload has a high dielectric loss (\( \varepsilon' \)) then a plain tunnel with the workload within it will form a good attenuator. If the workload does not have high enough dielectric loss (\( \varepsilon' \)) then additional lossy material must be added to the tunnel to improve its attenuation. Alternatively the choke tunnel could be made longer.

Currently, due the existing safety regulations, all microwave industrial equipment producers are very concerned about the efficiency of the leakage suppression and prevention devices attached to their microwave processing equipment.

Some examples are presented in the following and consist in already available patents.
Example 1 (Dudley et al. 1984)

Nowadays, one prior art approach to the suppression of microwave energy from a conveyorized microwave system is the solution to place a tunnel extending from the open-ended and line the tunnel with a lossy material which has to absorb the microwave energy as it propagates through the applicator. In this case, the product under microwave processing passes through the tunnel on a conveyorized system. One lossy material which can be used is a foamed glass but this material is fragile, dirty, and smelly and, therefore, is not compatible with food processing for example. Furthermore, the loss of foamed glass is relatively low so that an extremely long tunnel is needed in order to have effective leakage suppression from a relatively high power cavity. Other microwave absorbing materials can be used efficiently but all the process depends on the desired level of suppression and on the type of material which has to be processed.

Second option is the use of different lossy materials. The one to be used is a fluid that can be pumped around microwave transparent conduits in the tunnel so that the heat resulting from absorption can be removed by an external heat exchanger thereby reducing the temperature of the tunnel. Although this approach has an advantage over foamed glass in limiting temperature requirements of the tunnel, the plastic or glass tubes are easily broken. Also, the pumps and heat exchangers such as radiators are relatively expensive. Furthermore, this approach, like the foamed glass, requires that the tunnel be relatively long to provide adequate suppression and the cross-section through of the tunnel must be relatively small which can be impractical for oversized applications.

Another prior art approach to the microwave leakages suppression problem is to use a plurality of thin metal flaps that hang in a lossy wall tunnel. Product under microwave processing is passing through the tunnel on a conveyor and pushes the flaps aside. For this application the problem consists in the fact that when the tunnel cross-section has orthogonal dimensions that are substantially greater than a free space wavelength of the microwave energy and when product pushing aside the flaps is not sufficiently lossy, the flaps will not provide an effective seal as a standalone solution.

All of the above-presented approaches require the microwave energy entering the tunnel to be absorbed by some lossy material or reflected back to the applicator by the metal flaps. Accordingly, each of these approaches detracts from the efficiency of
the overall system because the available microwave energy must be split between the product and the microwave absorbing tunnel which will result in low efficiency microwave processing of the material.

Following the above solutions, the below U.S. Patent No. 4,227,063 (Figure 32) uses a plurality of conductive posts to provide an effective choke of microwave energy. Basically, that invention provides as leakage suppression device solution the existence of a tunnel providing a microwave choke for the fundamental frequency of the magnetron and a second tunnel connected to the second end of the first tunnel. The second attenuating tunnel comprising a first layer including ferromagnetic particles bonded to at least a portion of the inner surface of this tunnel and a second layer comprising a microwave transparent material covering the first layer.

Typically, the microwave oven would have access openings on opposing sides so that a conveyor belt could pass through. In such circumstance, a pair of tunnels would be connected at each access opening. Preferably, the first layer comprises ferrite particulate dispersed in silicone and the second layer is a sheet of Lexan or Teflon. The choke tunnel presents high impedance to the fundamental frequency of the magnetron which may typically be 915 or 2450 MHz in these industrial applications. The
ferromagnetic particles absorb broadband microwave energy in the second tunnel to suppress leakage of harmonics and other spurious out-of-band radiation.

**Example 2** (Ishino et al. 1997)

A different approach to this sensitive matter of reducing, under the standard limits, the microwave leakage at microwave processing devices with open ends is the use of ferrites. It is well known that ferrites absorb microwave energy such as those of 500 MHz to 12 GHz with the result of changing the microwave energy to a thermal energy. The ferrite is a sintered body having the spinel structure and it is a compound having the following general formula: MFe\(_{2}\)O\(_4\) (wherein M is a divalent metal such as Mn, Ni, Cu, Zn, Mg, Co, etc.).

The use of a sintered body of the ferrite for preventing the leakage of microwave in "microwave heating oven" has been disclosed in U.S. Patent No. 2,830,162. The microwave, however, can be absorbed more effectively by the powder of ferrite (ferrite powder) than the sintered body of ferrite. A mixture mainly composed by ferrite powder and an insulating material such as rubber has been shown for use in absorbing tunnel (U.S. Patent. No. 3,742,176).

The inventors of this device found that the effect of absorption of the microwave depends on both the frequency of microwave and the particle size of ferrite powder. Namely, the ferrite powder having a certain limited particle size can absorb more effectively microwave having a certain frequency.

**Example 3** (Wayne et al. 1980)

Further will be presented another suppression device which has been patented as US Patent No 4,182,946 (Figure 33). This invention describes a chocking system with potential benefits to the microwave processing industry. Microwave chokes have been employed at conveyor portals in many industrial applications. However, these known choke techniques all suffer from one or more deficiencies when applied to a conveyor portal in that they are not usable in continuous microwave treatment, are not effective at the frequency of the potential microwave leakage, do not provide a high degree of attenuation and/or are not readily usable with a conveying system.
Known choke means for use at conveyor entrances include partitions placed along conveyor means and being passed through a channel, as shown in Britton, U.S. Patent No. 3,151,230. The partitions passed through the channel in this manner serve as an electromagnetic short and attenuate microwaves incident to the partitions within the channel. However, such a system does not effectively prevent microwave leakage in the space between the edges of the partition and the channel wall.

A quarter-wave trap is disclosed in Fritz, U.S. Patent No. 3,166,663. Such an apparatus requiring the complicated technique necessary for maintaining the platform in position as it is moving through the entrance and exit channel leaves substantial problems in obtaining effective microwave leakage choking.

In microwave treatment where only a thin web is to be passed through a slot in the oven wall, corrugated choke solutions have been utilized to attenuate microwave leakage which would otherwise escape through the slot in the microwave oven. The corrugated choke includes protrusions from the slot shaped surfaces creating a reactance
causing attenuation of the microwaves. A benefit obtained from a corrugated or doubly corrugated choke is the attenuation of modes of oscillation other than the primary mode.

The attenuation of modes other than the primary mode is obtained by the placement of a series of protrusions along the surface encountered by microwaves propagated along the surface. Rather than interacting with two consecutive protrusions additional modes which interact with alternating protrusions are also attenuated.

It is an object of the present invention to provide a method and apparatus for substantially complete attenuation of microwaves in the area between a partition and a channel wall in a microwave choke at a conveyor port in a microwave oven.

It is a further object of the present invention to provide an apparatus for continuously moving large items through a microwave oven without dangerous microwave leakage.

It is a still further object of the invention to provide a safe, inexpensive and easily constructed choke for use in continuous microwave treatment of items placed on a conveying system for passage through a microwave oven.

Briefly, the apparatus and associated method of the present invention (US Patent No 4,182,946) includes channel walls forming a channel positioned at a portal through the oven wall and protrusions between the channel walls and the partitions peripheral walls. These protrusions with the role of providing microwave choking of the region between the channel wall and the peripheral walls of the partition. When a partition passes through the channel the large forward surface of the partition shorts microwaves incident this surface while microwaves which miss the partition and pass through the area between the partitions and the channel walls are attenuated by the interaction of the protrusions with the opposing walls. For attenuation to occur, at least two protrusions, when viewed in the direction of conveyor travel through the channel, must be overlaid by the peripheral walls of the partitions and the channel walls. The operation of the choke is such that when the ends of the protrusions are adjacent the opposing walls, so there is created a corrugated choke between the peripheral walls of the partition and the opposing walls of the channel. The length of the protrusions and the spacing between protrusions is essential to the effective operation of the choke at any given frequency. Varying the length and spacing of the protrusions will vary the frequency at which the choke will operate.
By maintaining at least one partition within the channel and allowing space between the partitions for the placement of items to be treated in the microwave oven, continuous choking occurs and items may be passed seriatim through the oven without the necessity for turning the oven on and off, or opening and closing a series of doors while moving the conveying system in a stop and go mode.

By providing the novel arrangement of a corrugated choke surrounding the partition and utilizing the partition itself, superior choking is obtained over previously known chokes.
CHAPTER 3

CURRENT DEVELOPMENT OF THE INDUSTRIAL MICROWAVE HEATING TECHNOLOGIES WORLDWIDE

Historically, microwaves have been used more for cooking and heating rather than drying at atmospheric pressure, although as always there have been some notable exceptions by using them for industrial applications.

To produce an overview about all the available applicators on the market is not an easy task as long as the specialized literature is not so developed due to the patented technologies which have been deployed in this industry. Even a long and detailed research of the online and libraries database cannot produce a better microwave industrial applicators overview than the one produced and presented by Perkin, 2006.

Note: text and figures omitted - copyrighted material
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3.1 Serpentine Microwave Drying of Webs and Sheets

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Note: text and figures omitted - copyrighted material
3.2 Microwave Drying of Regular Geometric Shapes: Blocks, Slabs, and Beds of Particles

Note: text and figures omitted - copyrighted material

3.3 Batch Ovens

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Note: text and figures omitted - copyrighted material
3.4 Continuous Ovens

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Note: text and figures omitted - copyrighted material
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Note: text and figures omitted - copyrighted material
3.5 **Microwaves Vacuum Dryers**

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Note: text and figures omitted - copyrighted material
3.6 Microwave Equipment for Wood Modification and Treatment

A significant example of the current development of the industrial microwave heating applications is the use of microwave in timber industry by the well-known Cooperative Research Centre for Wood Innovations. These applications were the reasons for conducting the research which makes the object of this thesis.

The CRC for Wood Innovation development team has as the main objective to further develop the application and use of microwave technology for timber processing and to promote the uptake and commercialisation of microwave technology in Australia and around the world. Strong benefits for the Australian timber industry and also for the international companies involved in wood processing arised from the particular emphasis on:

- Growth stress relief in fast grown plantation hardwoods.
- Microwave modification of wood to assist and accelerate wood drying.
- Microwave modification of wood to facilitate preservative impregnation.
- Production of microwave modified composite solid wood products.
- Production of an increased knowledge base concerning the interaction of microwaves on timber elements and the influence of these elements on phenotypic wood properties. (CRC Wood Innovations)

3.6.1 Growth stress relief in timbers

One particular direction this CRC was looking into the use of microwaves on treating the logs to improve recovery and utilisation of native and plantation grown hardwood. The plantation grown hardwood are known to have not so good properties comparing with the native forests but using this technology better results, from economical point of view can be achieved easily. The microwave technology proposed to be implemented involves the application of microwaves to rapidly heat and “soften logs” which can enable stresses contained in the log to relax and allow the timber to be processed with increased simplicity and productivity.
3.6.2 Microwave modification of wood to assist wood drying

This part of the project desire to model the distribution pattern of microwaves within a microwave applicator and within the wood to be modified. Understanding this pattern is crucial in order to ensure an even distribution of microwaves inside the dielectric material, wood in this case, can be achieved. Microwave conditioning can increase the permeability of the timber and facilitates immediate kiln drying of “green” timber, without the need for steam conditioning. Experimental results indicate a very significant fold reduction in drying time for messmate (E. obliqua) and other Australian wood species. Apart from quantum improvements in the control over drying processes, microwave conditioning can provide timber processors with significant reductions in cost associated with capital, space, energy and labour. (CRC for Wood Innovations)

3.6.3 Microwave timber modification for preservative treatment

Moreover, CRC Wood Innovations experiments demonstrated that it is possible to substantially improve the permeability of refractory wood species by intensive MW conditioning. After MW modification, timber can be impregnated with different types of preservatives and resins function of the desired purposed use of the timber pieces. These applications provide new opportunities for increasing the life of refractory species using preservative treatment and extending the utility of perishable species. The main objective of this application was to develop technology for impregnating any wood species and to produce preservative treated timber products suitable for a wide range of applications from posts and poles to sawn timber.

3.6.4 Microwave modified solid wood products

Another significant part of the CRC Wood Innovations (CRC WI) research and production capability is the production of microwave modified solid wood products. This project aims to develop and demonstrate the technology required for the production of new solid wood products manufactured from microwave-modified wood. The
application of very intensive microwaves to wood results in an expansion of the wood in cross-section (approximately 14%), with the formation of a multitude of micro-voids in the radial/longitudinal direction. The microwave treated material has radically altered acoustic properties, strength properties, dimensional stability and permeability. Permeability is increased by a factor in excess of 1200. The application of resin and compression back to the woods’ original dimensions leads to an increase in the woods strength, hardness, dimensional stability and durability.

The orientation of the microwave can be parallel or perpendicular to the fibre depends on the desired final result. It was recognized by the CRC WI researchers and also by the author of this paper during microwave computer modelling that the response/interaction with the microwave is significantly affected by this orientation of the electric field.

The conveyors and applicators used buy the CRC WI have a variety of benefits resulting from its features as well as some limitations, which are intended to be eliminated trough the continuous modelling and development. The choice of applicator was determined by:

- Cross section, shape and size of timber, and whether it is sawn or round wood
- Initial moisture content and intensity of energy needed
- Species- has multiple interrelated effects.
- Purpose of modification (permeability increase, accelerated drying, stress relief, or Torgvin production. (CRC Wood Innovations)

Torgvin is green timber that has been expanded through the creation of voids by high intensity microwave treatment. Wood that is treated in this way can have a softened, "spongy" feel. Treatment schedules using lower microwave power create tiny microvoids distributed throughout the timber.

Torgvin is an intermediary product in the manufacture of the wood-resin composite product Vintorg. After being treated to convert it to Torgvin, the wood is infused with resin, which percolates through the channels created by the voids. After the wood infused with resin is compressed back to its original dimensions in an industrial press and the resin is cured, the result is a wood-resin composite material Vintorg.
Vintorg looks like the original timber, but the infused resin confers improved structural properties and resistance to decay which makes this patented technology to be a very innovative and successful one.

In the following is a brief description of each applicator and their usual function.

### 3.6.5 The Tunnel Applicator

This applicator is able to preheat the timber is good for producing Vintorg from Radiata Pine, and gives even modification through the timber cross-section.

![The tunnel applicator (Hann et al. 2005)](image)

Possible applications for this system include:

- Low modification
- Optimal system for efficient production of Torgvin
• Wood internal stress relief

Also, the applicator configuration and its adjustable characteristics together with the conveyor speed, generator power and other parameters, permit its utilization for various other applications.

### 3.6.6 The Rotary Applicator

Another kind of microwave applicator is the one known as the “spit machine”. This applicator is able to be used for stress relief and permeability improvement of logs. Due to the design limitations of this unit, this applicator will only support the use of limited lengths of material from 2.4 to approx 3 m. Of course the next step in using this applicator is the development of a new version of it ready to process increased size timber pieces. The travel and stroke on the machine are such built that only the central part of the log are able to interact with the microwaves leaving two untreated zones on either side of the modified central portion as required by the beneficiary of this technology.

![Figure 35: The rotary applicator (Hann et al. 2005)](image)
3.6.7 The Box Applicator

This applicator has a uniform microwave interaction zone and provides low level preheating. This applicator provides the mild intensity treatment and is successful for producing Torgvin from numerous Eucalypts including *regnans*, *delegatensis*, *obliqua*, *globulus* and *nitens*.

3.6.8 The Taper Applicator

This applicator (Figure 36) is a refinement on the box applicator and is employed when very high intensity microwave radiation is required. Higher feed rates and shorter microwave interaction times are possible with this applicator. The taper section functions as a lens, concentrating the supplied microwave energy and reducing the zone of interaction between the microwave and wood.

Careful observation and attention is required when using both of these applicators as they are more susceptible to arcing, as a result careful examination of applicator surfaces is needed along with thorough cleaning after use.

Figure 36: Taper applicator (personal photo taken at CRC Wood Innovations)
3.6.9 Intermediate sized conveyor

This conveyor is used in conjunction with the Box and Taper applicators. Installation can be carried out with the vector $\mathbf{E}$ parallel or perpendicular to the grain orientation, by this having a total of 4 configurations for this unit. The taper applicator is used to provide a higher intensity of MW energy in a shorter timeframe, allowing for more precise control of the modification process. By monitoring the power inputs transmission and reflection, the amount of energy used to heat the timber and affect modification can be estimated with better accuracy than in the tunnel applicator.

Figure 37: Intermediate sized applicator (Hann et al. 2005)

In addition to this kind of applicators, CRC has had a new over-sized conveyor constructed and tested. This conveyor is able to mount both the taper and box applicators in a manner similar to the intermediate-sized conveyor. The new conveyor
system is unique in having a positioning system, which allow timber careful placement within the microwave interaction zone. Further, this applicator allows the processing of larger cross-sections of sawn material, with use of a conveyor suitable for use on sawn material from 20 x 20 mm cross-sections up to 160 x 160 mm timber. This applicator has an extendable length, and due to the ancillary safety requirements has a long wide footprint when it is connected to the microwave generators.

Moreover a special purpose “Microwave splitter” applicator was developed for use with the 30 kW microwave generator. This splitter was developed to apply microwaves to two faces of the timber utilising a single microwave generator in a single pass.

The overall design of the microwave conveyors and applicators has flexibility in mind with either generator (30 or 60 kW units) able to be utilised. The total number of microwave conveyor/applicator combinations depends on the client requirements and can be easily adapt and transform to best fit the needed wood processing techniques (Hann et al. 2005).
CHAPTER 4

ELECTROMAGNETIC MODELLING OF MICROWAVE EQUIPMENT AND PROCESSES

4.1 Introduction

Any research and development microwave company cannot avoid the need for modelling of new microwave equipment proposed to be used in industrial application. This process sometimes needs strong and powerful computational systems due to the electromagnetic processes complexity.

Computer simulation of microwave heating remains a relatively new and unexplored arena: industrial engineers either lack reliable information on modern computational opportunities, or are under influences of commercial, misconceptions, and myths (Yakovlev 2000).

Nowadays it is recognized that an important element of microwave process development and system design is the capability to model electromagnetic interactions. An understanding of the variation of the dielectric properties with temperature and processing state is crucial for simulations and process modeling. Computer modeling can be used to optimize generator or applicator system design, establish achievable processing windows, and conduct realistic process simulations for given dielectric properties, sample size, and desired processing conditions (NMAB, 1994).

4.2 Development of Computerized Numerical Microwave Modeling

Further, Yakovlev mentioned that there are two contributing factors in today’s fast development of computerized numerical microwave modeling: one is the advances
in computer chips which are doubling performance every 18 months and a still faster advancement of memory (disk) capacities noticeable doubling every nine months and second is the advances in numerical algorithms. The latter can be characterized more by revolutionary steps than by a continuous evolution, and it is estimated that a doubling of capability and reliability has occurred about every three years, since the end of the ‘80s. At the same time, it was noticed that as new options are made available, modeling software prices have not changed much, due to increased competition and market penetration.

Nowadays the challenge before the designer involved in the development process of microwave equipment and techniques is how soon they can learn to apply modeling theory and technology in a way that will result in improvements in industrial and consumer microwave products and processes.

Microwave modeling has already completed several years of preliminary development and increasingly rapid development of end uses is now expected. Noticeably, the use of Electro-Magnetic (EM) modeling software is increasingly implementing as a discipline in the universities courses. Presently, advanced modeling projects are mainly confined to joint university-industry studies and have only scratched the surface potential for end-product improvements. With the rapid evolution in computers and software and the interdisciplinary character of microwave heating technology, there is a great need for engineering staff to learn and perfect modeling techniques. But, even now there are major opportunities waiting for companies who take an early lead in modeling development.

As it is now successfully used in industry, modeling consists of analyzing and solving specific, limited problems. While that alone makes it a useful tool, it was discovered that modeling could be very well suited to detailed study of smaller areas within a load, oven or industrial applicator. Such detailed sub-studies can focus on a specific problem resolution or can be combined with a series of sub-studies to optimize the overall system and/or load performance. The use of sub-studies significantly reduces their complexity and runtime. An additional advantage with this approach is that some sub-studies may be quite small, allowing much greater modeling detail and accuracy. A further, very important aspect is that sub-studies are useful not only for new developments but also for improvements of parts of already existing systems.
Together with the development of new microwave equipments and techniques it was noticed, by many industry users, that studying of tolerances, metal joints and their local overheating or microwave leakage, risk of arcing or overheating of supports, microwave leakage at the door, etc., the computer modeling became today their most useful applications. When two or more sub-studies produce the desired result, they may be joined into a new modeling scenario, such as for studies of the impedance matching of a larger part of the whole system. Fewer complete scenarios will then need to be run, and the total optimization becomes more reliable by this the developers and finally the industry being able to get a higher margin for their investment.

The current advances in electromagnetic software can be summarized by the following examples of recent and forthcoming extensions of some software packages:

- Simplified inputs of 3D geometries, such as reading industrial CAD files.
- Direct access to various absolute and averaged result data, which can serve as inputs to external goal function calculators.
- Interfaces to external optimizers, which apply a user-defined goal function to automatically adjust the scenarios.
- Advanced conformal mesh generators, to be used with materials like susceptors and detailed thin metal structures in containers, which are typically difficult to model reliably.
- Improved models of waveguide feeds, etc., simplifying the creation of sub-studies.
- Built-in thermal modules, and interfaces to external thermal modules, permitting automated variation of media parameters as a function of temperature.

These extensions represent a revolution in modeling for heating applications, and will improve its convenience and reliability while at the same time reducing the engineering work time. Even if some of the optimizations may take a day or more with today’s computer speeds, the advances in computer and parallel processing are likely to continue to reduce that inconvenience.

Several commercial software providers are now ensuring continuity, quality and competition to the benefit of users both in industry and academia. The fast pace of their developments may, however, continue to be challenging to an industry which may lag in their appreciation and use of the new strengths (Yakovlev, 2001).
4.3 E-Field 3-D Modeling and Simulation Techniques

Despite all the progress in numerical mathematics and computational technologies, computer simulation of processes and systems of microwave power engineering remains a new and unexplored arena for most practitioners. Because at the beginning the microwave were used mainly in military and telecommunication applications, engineers dealing with microwave non-communication applications currently seem to lack not specific technical data but general information on modern computational opportunities and their benefits.

By using E-field 3-D modeling and simulation techniques, one is able to precisely simulate the shape and intensity of applied E-field heating using complex mathematic algorithms and computer-aided simulation technology. By this guaranteed equipment heating, drying performance and reliable operation for a full range of products specified can be obtained.

At the same time, a number of modeling tools do allow one to get valuable data about the characteristics of the considered system prior to constructing a physical prototype. In order to create an image of the current development of the electromagnetic processes modeling techniques, an update of the database of the modern electromagnetic (EM) software suitable for the modeling of microwave heating is needed as well as an outline of a few conceptual and practical issues associated with the efficient use of these simulators.

4.4 Software Database

One scientist involved in the evaluation and comparison of these software is Prof. Vadim Yakovlev, which mentioned that the market for the modern EM modeling software is very dynamic due to the strong competition among the vendors. Since all the solvers were originally developed for the military, communication and high-speed electronics, these rapidly growing sectors are permanently demanding more adequate and sophisticated computations and further the new microwave applications fields are very interested as well.
Many features of these newly developed tools can be of help for the practice of MW power engineering. Nowadays, the list of pieces of software suitable for this field includes 17 names of full-wave 3D EM simulators. These commercially available codes are produced by 16 vendors from 7 countries in Europe, North America, and Japan.
Table 1: Modern modeling software applicable to simulation of the test problems, as of September 2001 (Yakovlev, 2001)

<table>
<thead>
<tr>
<th>Vendor and Code</th>
<th>License &amp; Maintenance</th>
<th>Kernel Method; Operating System</th>
<th>Status in MW Power Engineering</th>
<th>Features of Performance, System Requirements, etc</th>
</tr>
</thead>
<tbody>
<tr>
<td>CST, GmbH <a href="http://www.cst.de">www.cst.de</a> MAFIA 4.1, Microwave Studio 3.2</td>
<td>$30-50,000 14%</td>
<td>Finite Integration Technique; UNIX, Windows 95/98/2000/NT4 Windows 95/98/2000/NT4</td>
<td>Actual use.</td>
<td>SAR. MAFIA: up to 20 mil. cells. Optional temperature analysis. Microwave Studio: PBA, non-uniform meshing, AutoCAD and ACIS export/import, CAD design, optimizer,</td>
</tr>
<tr>
<td>Company</td>
<td>Price</td>
<td>Method</td>
<td>Operating System</td>
<td>Use</td>
</tr>
<tr>
<td>------------------------------</td>
<td>----------------</td>
<td>-----------------------------------</td>
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<td>--------------</td>
</tr>
<tr>
<td>IMST, GmbH</td>
<td>$12-20,000</td>
<td>Finite Difference Time Domain Method; UNIX, Linux, Windows 95/98/2000/NT4</td>
<td>Actual use</td>
<td>SAR. Auto CAD import (limited to 3D boxes). 300 MB hard-disk space.</td>
</tr>
<tr>
<td>Remcom, Inc.</td>
<td>$15,000 $3K</td>
<td>Finite Difference Time Domain Method; UNIX, Windows 95/98/2000/NT4</td>
<td>Actual use</td>
<td>SAR. iSIGHT optimization d. Multiprocessor for FDTD</td>
</tr>
<tr>
<td>Software</td>
<td>Price Range</td>
<td>Method</td>
<td>Operating System</td>
<td>Features</td>
</tr>
<tr>
<td>--------------------------</td>
<td>-------------</td>
<td>---------------------------------</td>
<td>-------------------</td>
<td>-----------------------------------------------</td>
</tr>
</tbody>
</table>

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aAlso distributed by Vector Fields, Inc. under the name Concerto.
cBy Altair Engineering, Inc., www.altair.com
dEngineous Software, www.engineous.com
Table 1 contains the references to the solvers, which currently are used around the world and have already got the intent look of the engineers designing the microwave heating systems. Other codes from this database not shown in this table may currently be not as suitable as these ones: some of them run only under UNIX operating system (EMFlex by Weidingler Associates, Inc.), others are present only on the regional markets (like the Japanese codes MAGNA/TDM and JMAG-Works). By the term “actual use” was intended to underline the fact that the particular software has been used at least once in some R&D or industrial microwave heating projects, “potential use” indicates that the solver has passed the selection criteria, but the examples of its application in modeling of MW thermal processing are unknown (Yakovlev, 2000).

It was noticed that among the kernel computational methods, Finite Element Method (FEM) and Finite Difference Time Domain (FDTD) dominate; Transmission Line Method, usually considered quite similar to FDTD, is also available. FEM algorithms have been limited to the problems that are electrically not large because of the necessity to use too much memory.

Codes, which are essentially electromagnetic and able to determine at least patterns of dissipated power, are analyzed below. Each code exists in either one, or several versions for various operating systems. It is known that a few years ago, UNIX associated with workstations or supercomputers was the only option for efficient EM codes. Today, 14 out of 16 packages work under Windows NT.

The last column of Table 1 contains an indication on the software status in microwave power engineering. Kernel methods used in each code are referred to in the same column as well.

As Yaklovev mentioned it seems to be reasonable to suggest that for practitioners in the microwave power industry it would be feasible to have software with the capability of calculating the dissipated power of the excited fields as a minimum. Finding eigenfields may not be enough for the purposes of industrial design since these data require certain interpretation.

Further, there are indications to the key parameters, which can be calculated and visualized: dissipated power and Specific Absorption Rate (SAR). Currently, SAR is not available in all codes; however, vendors say that since calculating one on the basis of the other is simple, this would be added if any customers request it.
Interface, a highly important software element, appears to be very different in various codes. Agilent and Ansoft have developed for their codes the own advanced interfaces. Microwave Studio, Empire, and QuickWave-3D offer advanced functions for export/import data to work with some CAD software (like AutoCAD).

Another important feature is an optimization option. CST MWS, Agilent HFSS 7.0, Ansoft HFSS 5.5, QuickWave-3D 1.9, and XFDTD 5.1 possess it in some form. The option implements a certain procedure of computer optimization, that is, a subsequent solution for various scenarios with the choice of parameters supposed to be the best in accordance with some specified criteria. Running this option may take much time, but it might be useful to eliminate the need for modeling of various configurations and types of equipments.

Two vendors, CST Microwave Studio and QWED QuickWave-3D have implemented in their products practical solutions of how to overcome the major disadvantage the classical FDTD possesses in comparison with FEM: the stairs-like approximation of the mesh cells. The incorporation of the so-called perfect boundary approximation in Microwave Studio allows an accurate modeling of curvilinear regions.

However, today the time domain algorithms associated with the techniques for overcoming the difficulty conforming to curved surfaces (the FIT with the Perfect Boundary Approximation suggested by CST for Microwave Studio (MWS) and the conformal FDTD developed by QWED and implemented in QuickWave-3D (QW3D)) may appear preferable for many classes of problems in MW heating typically involving objects with complicated boundaries. These algorithms are able to handle larger problems, need less memory, are generally quicker than FEM algorithms, and are capable of naturally animating the field and power propagation in the structures.

User-friendly intuitive graphical interface can be named among other advantages of MWS. Couple example of successful use of this software have been reported by Toshiba Research Europe Ltd., The Boeing Company, Motorola (Switzerland) AG, Radio Frequency Systems, Inc., and not the last the strong alliance with Agilent Technologies. The CST software history is shown in Table 2:
Table 2: CST MWS Software development history (Yakovlev 2005)

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1975</td>
<td>Start of Studies on Finite Integration Theory (FI)</td>
</tr>
<tr>
<td>1980</td>
<td>First Time Domain Code with particles</td>
</tr>
<tr>
<td>1983</td>
<td>MAFIA Collaboration</td>
</tr>
<tr>
<td>1989</td>
<td>MAFIA Release 3</td>
</tr>
<tr>
<td>1992</td>
<td>Release 3.1 (macro language, full parametrization)</td>
</tr>
<tr>
<td>1994</td>
<td>Release 3.2 (optimization)</td>
</tr>
<tr>
<td>1997</td>
<td>MAFIA Release 4 with GUI</td>
</tr>
<tr>
<td>1998</td>
<td>First version of CST MICROWAVE STUDIO®</td>
</tr>
<tr>
<td>2000</td>
<td>First version of CST DESIGN STUDIO™</td>
</tr>
<tr>
<td>2001</td>
<td>First version of CST EM STUDIO™</td>
</tr>
</tbody>
</table>

4.5 CST Microwave Studio - the Chosen EM Modeling Package

After completing a cost-features-user friendliness assessment of the available EM modeling software on the market, CRC for Wood Innovation has chosen for microwave modeling and simulation software the CST Microwave Studio 5.1 which was used and also made the principal tool for the development and evaluation of the new microwave equipment suitable for wood modification. The computer modeling and simulations were conducted with the aim of developing new microwave equipment and to check and confirm its suitability for wood modification and treatment.

The reasons for choosing this software was that CST Microwave Studio is proved to be an excellent tool for design engineers for the utilization of high frequency 3D electromagnetic field simulation.

The use of this software not only has the potential to save prototyping time and costs but also provides invaluable insight into whether the device is likely to be viable and if further investment is warranted. To enable engineers to make these decisions the used version, v5.1 of CST MICROWAVE STUDIO (CST MWS) provides major enhancements. In particular, the implementation of 64-bit technology and the availability of the choice between transient and frequency domain simulation, and
between Cartesian and tetrahedral meshing in the latter enable considerable access to cutting-edge technology (Computer Simulation Technology 2005).

4.5.1 CST MWS features and benefits

To create an overview of this software it has to be mentioned that it is a numerical simulator for general high frequency 3D EM simulation and is based on the Finite Integration Technique (FIT). This is a versatile approach that can be and is consistently applied to all kinds of EM simulation tasks, from statics to the optical regime, to other physical problems such as thermodynamics or elastodynamics. In addition, FIT can be formulated on any kind of grid, Cartesian or general non-orthogonal, in both the time domain and in the frequency domain.

The application range of the simulation software is large, encompassing antennas, filters, cavities, couplers, connectors, transitions, radar cross section, electromagnetic compatibility, signal integrity, specific absorption rate and medical applications, to name but a few.

In the following will be presented some of the main characteristics of the CST MWS the chosen EM modeling software.

One important feature, which can help during the modeling-simulation-design-test processes, is the Interoperability/Data exchange. The CST MWS interface allows fast modeling of complex structures, promoting design intent capture and implicit parameterization of geometrical models. A wide range of interfaces to formats of mechanical CAD tools is available.

Reliable CAD interfaces are an important requirement to augment the design engineer's throughput since the redrawing of existing structure parts has to be regarded as a major drawback. CST MWS is renowned for its excellent CAD-data import capabilities and the sophisticated healing mechanisms which recover the integrity of flawed or non-compliant data. The latter aspect is particularly vital as the presence of one corrupted element can prevent the usage of the whole part (Computer Simulation Technology 2005).

CST MWS features a multitude of CAD import options. An example of how this wide range of interfaces to mechanical CAD tools allows the import of complex
models is shown in Figure 38. This version v5.1 modeler enables the subsequent parameterization of imported CAD-data, and thus its optimization. Interfaces to other EDA software tools include Cadence®, Allegro®, and a tight alliance with Agilent introduces 3D EM simulation to the mainstream.

Data exchange options include:

- 3D Import/Export: SAT, STEP, IGES, STL
- 3D Import only: Pro/E®, CATIA 4®, CoventorWare
- 2D Import/Export: DXF
- 2D Import only: Agilent ADS, Cadence Allegro, GERBER, GDSII, Sonnet Suites

Moreover, the 64-bit capability takes to the next level the use of modeling software for microwave industrial applications.

Despite CST MWS’ ability to deal with electrically large structures, it has, up until now, been limited by 32-bit operating systems to approximately 20 wavelengths in each spatial direction. However, the implementation of 64-bit technology in version 5.1 enables much larger electrical problems to be tackled, with currently available standard
64-bit PC technology (8 GB of RAM) beyond 30 wavelengths in each direction, and theoretically much farther.

In addition to the transient solver, an eigenmode solver is offered for loss free and lossy resonant structures. A modal analysis approach extends the capabilities of the eigenmode solver to the calculation of S parameters of filters, for example. Also, the eigenmode solver is equipped with periodic boundaries to calculate the dispersion of traveling wave tubes, frequency selective surfaces or other crystal type structures.

Also, this software features a Model Order Reduction (MOR) solver, a particularly fast approach to derive the S-parameter of resonant structures directly and will be useful for filter design. This is an advanced mathematical approach which directly calculates the S-parameters without calculating the fields. The principal application is the filter design, where tremendous speed-ups can be achieved. This particular tool was used for the modeling and design of the microwave leakage suppressor.

The Transient Solver is the flagship module of CST MWS. It is very flexible and can be applied to most electromagnetic field problems. Broadband simulations can be performed with an arbitrary fine frequency resolution. Field results for many frequencies can be derived form one single simulation run.

The Eigenmode Solver is of particular interest in the design of filters, diplexers, and cavities. It efficiently calculates a finite number of modes in any loss-free electromagnetic device. Periodic boundaries enable the study of slow wave (e.g. TWT's) and crystal type structures.

CST MWS's Eigenmode Solver also features an extra post processing option for highly resonant structures, the Modal Analysis. After the modes of a device have been calculated, this very efficient technique can derive the S-parameters of the filter with little additional simulation time.

The Frequency Domain Solver is particularly useful for lower frequency applications, i.e. the structure size is much smaller than the wavelength and for periodic structures like antenna arrays. For antenna arrays CST MWS offers a Floquet-mode boundary condition that not only improves accuracy and simulation speed, but also distinguishes between main and grating lobe. Scan angle analysis becomes an easy task.

Which solver to choose during the various simulations and modeling techniques cannot be easily answered, besides the hints given above, the Figure 39
differentiates between the application ranges of CST MICROWAVE Studio’s solvers by the Q factor. However the lines cannot be precisely drawn and it depends on the desired result of the modeling or sometimes by the designer experience.

Figure 39: CST MWS solvers (Computer Simulation Technology 2005)

CST simulators have proven their outstanding accuracy and speed in numerous published benchmarks: Vivaldi antenna - Microwave Engineering Europe, 2000; Dual mode filter - Microwave Engineering Europe, 1997; Four-port waveguide coupler - Microwave Engineering Europe, 1995.

The method of calculation used by this software is the FI-Method. The combination of the proprietary PBA (Perfect Boundary Approximation), which belongs to the CST company, technique with the unbeatable efficiency of the Finite Integration method (FI) is the basis so many companies are using this software. During the simulations was noticed by the CST MWS producers that its numerical effort increases more slowly with the problem size than other commonly employed methods and this is a huge advantage which plays an increasingly important role as microwave modeling problems become more complex and frequencies rise.

Another available solver included in this software is the frequency domain solver that complements the time domain capabilities. This facilitates the study of periodic structures. Besides the increase in performance it also enables the investigation of plane wave incidents from arbitrary angles while an adaptive frequency sweep speeds
up broadband investigations by reducing the number of simulations necessary to achieve the desired accuracy.

Also significant is that, in the frequency domain, users may freely switch between the standard Cartesian PBA meshing and tetrahedral meshing. Although adaptive meshing is available for both mesh types, the Cartesian mesh can be easily manipulated by hand or trained through the adaptation process. The non-structured tetrahedral grid is advantageous for studying components with small, localized features.

Besides the known approach of meshing curved surfaces by segmenting them first, the CST’s tetrahedral mesh producer also allows true surface meshing for increased accuracy. The modeler will benefits from the sophisticated post processing mechanisms, which enable highly automated access to simulation results that can be used individually or combined within mathematical expressions to derive arbitrary goal functions for automatic optimization. For huge computational problems to reduce the time of delivering results, distributed computing is one further means of increasing performance. Parameter studies and optimization runs can be distributed over the network and results are collected and evaluated in one central front-end. After this step, new parameter sets for the next turn of simulations can be set up and distributed again on participating computers thus cutting down simulation time significantly.

SmartGrid is another feature which complements the software. CST Microwave Studio features proprietary techniques for geometry generation. First of all there is the PBA (Perfect Boundary Approximation)® that describes arbitrary geometries conformably on a Cartesian grid. The Thin Sheet Technique (TST) extends the capabilities of PBA by enabling the independent treatment of two dielectric parts of a cell, separated by a metallic sheet. By having this at his disposal a user can model now easily structures like arbitrarily shaped housings or thin inclined shields.

As mentioned above one of the reasons for choosing this software by the CRC for Wood Innovations was the Interface which was noticed to be as user friendly as possible. An intuitive, native Windows based GUI, makes even the beginners immediately feel at ease with the program. New users are escorted through the program by a quick start guide and a collection of online tutorials. The advanced ACIS kernel 8.1 enables amazingly easy CAD modeling. A strong graphic feedback further simplifies device definition. Simulation runs and post-processing can be controlled, via OLE automation server, using applications such as Excel, Matlab, and PowerPoint.
At last but not least, another feature has to be mentioned. This is the Automation/Optimisation&Parameterisation. During more complex simulations where more that one parameter has to be often changed it is a great help the use of the fully automatic CST Microwave Studio optimizer with which every parameter can be varied and even complicated. These new and powerful optimization strategies allow optimization even for multiple parameters in a reasonable length of time resulting in exceptional time value.

4.5.2 CST MWS features summary

A summary of the technical properties of the CST Microwave Studio Software has to be done in order to support the decision behind the choosing of this EM modeling tool (Computer Simulation Technology 2005).

**Transient Solver Module**

- Broadband calculation of S-parameter and antenna problems
- Broadband Gaussian or User-defined time excitation including digital signals
- Library for excitation signals
- Multi signal functionality for simultaneous excitation
- Excitation with port modes, discrete elements (inner ports), and plane waves (also circular and elliptical polarized)
- Port mode and impedance calculation by 2D-Eigenmode Solver, incl. Multipin-Ports
- Boundary conditions: electric, magnetic, open (PML)
- Lumped elements including RLC and diode models
- TDR capabilities like time dependent impedance
- De-embedding and renormalization of S-parameters
- AR filter analysis for resonant structures
- Time Domain and Frequency Domain (multiple frequencies in one simulation run) monitoring of electromagnetic fields (E, H, J, energy, powerflow, farfield)
- Specific Absorption rate (SAR) calculation
• Farfield calculation (2D, 3D, gain, field pattern, polarisation, Ludwig II/III transforms, axial ratio, angular beam width, phase plots...)
• Time domain farfield probes
• Bistatic and monostatic Radar Cross Section (RCS) Calculation
• Lossy and anisotropic dielectric materials
• Frequency dependent (dispersive) and gyrotropic (ferrite) materials
• Conductor surface losses with skin effect
• Multilevel Subgridding Scheme™ (MSS)
• Exclusion of PEC materials from calculation domain
• Simultaneous port mode calculation for two ports (requires Windows network with file server and clients within one domain)

**Eigenmode Solver Module**

• Eigenmode calculation
• Modal Analysis to derive S-parameters from high Q structures
• Automatic mesh generation (expert system) and adaptive mesh refinement
• Q-factor calculation
• Eigenmode calculation in the presence of lossy materials
• Periodic boundary conditions with arbitrary phase shift

**Frequency Domain Solver Module**

• Choice of Cartesian or tetrahedral meshing
• Adaptive Frequency sweep
• Automatic mesh generation (expert system) and adaptive mesh refinement
• SAR calculation
• Farfield calculation (2D, 3D, gain, angular beam width...)
• Port mode and impedance calculation by 2D-Eigenmode Solver
• Lumped elements including RLC circuits
• De-embedding and renormalization of S-parameters
• Periodic boundary conditions with arbitrary x-phase shift
• Periodic port modes
Model Order Reduction (MOR) Solver Module

- Fast Calculation of S-parameters from high Q structures
- Automatic mesh generation (expert system) and adaptive mesh refinement

All Solver Modules

- Powerful optimiser and automatic parameter sweeps
- OLE automation server
- VBA macro language
- Precise geometry description due to Perfect Boundary Approximation™ (PBA)
- Thin Sheet Technique™ (TST)
- Fully parametric ACIS R12 based modelling
- Import/Export of 3D CAD data with automatic healing options (SAT, STL)
- Import of planar structures (DXF)
- Import of Agilent Momentum layouts
- Creation of Agilent ADS Data Access Components (DAC)
- Video display of field distributions
- Export of Touchstone® files and any field results
- Geometry and mesh export to MAFIA 4
- Automatic expert system based mesh generation and adaptation
- Template based result management
- Material library
PART II

RESEARCH METHODOLOGY, DEVELOPMENT OF MICROWAVE EQUIPMENT AND THE SUITABILITY TESTS FOR WOOD MODIFICATION
CHAPTER 5

RESEARCH METHODOLOGY

5.1 Defining the Research Problem and Objectives

The review of the specialised literature demonstrated that microwave is a powerful method for heating dielectric materials. The challenges of using microwave power in various heating applications consist not only in the numerous complicated physical phenomena involved in the process but also in the development of suitable equipment. It has been shown in the previous chapters that currently there is an increasing trend in using microwave in processing industry, being used mainly for heating and at a less extent for drying. Several representative examples of available industrial equipment confirmed the fact that function of the desired application, the microwave equipment has diverse components, characteristics and functions. For instance, microwave modification of wood requires the application of very intensive microwave energy (up to 300 kW/cm²) for very short periods indicating that no microwave equipment used for other applications is suitable for microwave processing of wood.

The microwave wood modification techniques are at their early development stages. Cooperative Research Centre for Wood Innovation is the leading research group in the world which investigates the application and use of microwave technology for timber processing in order to promote the uptake and commercialisation of microwave technology.

As part of the CRC for Wood Innovation research program, the study developed within this paper dealt with the following research problem:
**Research Problem**

Development of new equipment (applicators and suppressors) utilising a range of different frequencies (between 0.4 to 24 GHz) to achieve high electromagnetic intensity and to ensure its subsequent release in the wood.

In order to narrow the aspects of the primary target of the research, the subsidiary problems were formulated:

**Subsidiary Research Problems**

P1. Design and optimise microwave applicators able to achieve uniform treatments of dielectric materials in cross section without generating substantial structural defects.

P2. Develop a practical way able to complement the microwave applicator and to highly reduce the energy reflection to the generators.

P3. Design and develop a microwave suppression leakage device for continuous wood flow microwave industrial systems.

According to the above research problems, the main research objectives were:

**Research Objectives**

O1. Perform modelling and simulation of the microwave energy interaction with wood material by inventing and using different technical structural and dimensional arrangements of the microwave equipment.
5.2 Approach to the Research Problem

The research problems posed above expressed a need for more thorough understanding of various technical and computational issues involved in the microwave processing of wood in order to achieve the optimal function of this process. Hence, two research approaches (qualitative and quantitative) were argued for in order to meet the research objectives.

The qualitative research approach was performed as situation analysis or background information based on the extensive literature review conducted in Part I of this project. Background data were derived from articles, books, journals and web sites. This review of the literature offered a deep insight into many aspects of microwaves and wood.

The objectives of the qualitative research were:

- To emphasise the imminent potential of microwave energy in wood industry;
- To gain awareness and understanding of the main aspects of microwave systems;
- To create an overview of the current microwave development in industrial processing;
- To understand the need and the principles of the electromagnetic computer modelling.

The quantitative study was based on computer modelling and experimental tests. When a complex microwave heating process such as the ones used to microwave wood, is analyzed experimentally, trial and error processes are inevitable due to the complexity of the interrelationships among the above parameters. The electromagnetic modelling, simulation, analysis and design tools have become of supreme importance in
the cost-effective research and development of the industrial microwave heating systems, due to the challenges that microwave applications confront and the high costs and time consuming of the experimental methods. The computer modelling was used to develop and refine microwave applicators that generate uniform electric field patterns within rectangular applicator profiles and to develop a microwave leakage suppression device using microwave composite absorbing materials, a water circulating and cooling system and microwave reflecting metal tiles and mesh. Computer-aided modelling was also used as a tool to investigate how microwave applicator design affects energy distribution and the shape of the modification zone. Modelling helped create optimal designs for microwave applicators, without a prolonged trial and error process. The CST Microwave Studio package was chosen to perform the modeling due to its value costs-performance quality and excellent user friendliness, which permits graphical definition of any 3D structure, mesh generation and specification of simulation parameters.

Through the quantitative study two goals were accomplished: first, models and physical microwave equipment for wood modification were developed; second, the importance of this research to the timber industry was indicated and some recommendations for the further work formulated.
CHAPTER 6

COMPUTER MODELLING OF THE ENERGY DISTRIBUTION WITHIN WOOD THROUGHOUT MICROWAVE PROCESSING

Microwave processing technologies become more and more essential within the industry due to their technical and economical advantages. To optimise and minimize the project design engineers’ work, modelling/simulation of the microwave energy interaction with dielectric material represents an indispensable tool.

The aim of this research work was to design and optimise microwave applicators able to achieve uniform treatments of dielectric materials in the cross section without generating substantial structural defects. Through 3D electromagnetic simulations, a practical and innovative way capable to control the intensity and distribution of the microwave treatment pattern within dielectric material was theoretically accomplished and presented within this chapter.

The theoretical computer simulation values were used as indicative facts for the starting point in experimental testing.

6.1 Introduction

High intensity microwave treatment is able to create quantitative and qualitative changes in dielectric materials structure, which might significantly contribute to
both the new feature of materials and to reduce processing time. Inside wood, microwave energy is converted to heat, creating steam pressure in the structure cells, in the case of moist wood. This causes some cells to break open, creating microscopic voids, which allow the moisture to escape more easily, and the wood to dry more quickly. The most drying models confirm that the tortuosity of the moisture transport path, associated with sometime high wood density or low moisture permeability, together with wood’ non-uniformity and anisotropy are important control parameters during the diffusion-controlled drying process.

However, in order to take full advantages of microwave processing, intensity of microwave power per volume, the rate of drying, loading period; maximum temperature in the core and moisture removing cycle have to be carefully selected to reduce structural deformation.

Among other factors, the various deterioration mechanisms during microwave drying of porous media, like wood or plaster, cement slurries or concrete, ceramics etc., moisture evaporation and pressure-gradient mass transfer play a dominant role.

Each application involves careful consideration of the intensity of the supplied microwave energy. For instance, throughout microwave processing of ceramic materials cracking, distorting and warping are problems that are usually caused by drying too fast or unevenly. If the dielectric is heated too fast, the pressure from water vapour inside the piece can cause cracking. It is important to carefully remove all of the physical water so that the piece will not crack or explode when heated. The research clearly shows the benefit of using lower kernel temperatures to dry ceramics with respect to stress cracking. As a result, the intensity of microwave power should be carefully selected and the amount of moisture removed during pre - drying should be limited to the stress crack damage which is caused due to the high materials temperature and drying rate /moisture removal (Metaxas and Meredith 1993).

On the contrary, the novel microwave technology for wood structure modification employs high intensity power per unit volume to create microscopic changes in timber. This technology capable to increase wood permeability several thousand times to accelerate drying time and preservative impregnation, microwave conditioning for relaxation of growth stresses in logs, and generation of new solid wood products (CRC Wood Innovation 2003).
Conceptually, the major factor in the intensification of microwave drying is the applying of a large amount of heat per unit time, which ensures a high phase transition rate. Practically, controlled application of microwave energy has been shown to selectively rupture the wood structure creating radial pathways in the wood (Figure 40) through which moisture may readily move (CRC Wood Innovation 2003).

![Figure 40: a) Unmodified Blue Gum (Eucalyptus globulus); b) Microwave modified Blue Gum (Eucalyptus globulus)](image)

Each application involves adjustment of the intensity of the supplied microwave energy. This has to be made in such way to control the number, dimension and distribution of the micro-voids. The wood micro-voids are formed as a result of the ray cell rupture due to the resulted high internal pressure. In addition, the extent of modification of wood by microwaves depends on the treatment time and the power supplied. These requirements provide challenging problems in the design and optimisation of the microwave applicators shape and size which affects the intensity and distribution of energy and hence, the profile of the modification zone. Besides, the wood properties and geometry may also affect the magnitude and distribution of the absorbed energy (Vinden and Torgovnikov 2000).

When a microwave heating process is analysed experimentally, trial and error processes are inevitable due to the complexity of the interrelationships among the above parameters. The electromagnetic modelling, simulation, analysis and design tools have become of supreme importance in the cost-effective research and development of the industrial microwave heating systems, due to the challenges that microwave
applications confront and the high costs and time consuming of the experimental methods.

This chapter presents the work on the modelling and design of a microwave pretreatment applicators system by investigating the effect of its configuration and size on the energy distribution and the shape of the treatment zone within dielectric materials. The computer-aided modelling was used as the principal tool to examine the energy distributions in dielectric specimen and the maximum power loss behaviours as the size of the tunnel applicator varies. Firstly, the chapter presents the 3D electromagnetic simulations of the energy distribution within piece of dielectric by using diverse dimensions for the microwave tunnel and a specific configuration of four tapered radiators. Subsequently, based on the simulation results and physical and practical facts, the optimal tunnel width was determined and considered for the experimental use. Finally, the optimisation was further performed by experimental trials.

6.2 Simulation and Optimisation of the Energy Distribution within Wood, Generated by Different Size Applicators

In the microwave heating applications for long or bulky products are going to be processed, the use of the multimode cavity applicators is the only option. Unlike the TE10 travelling mode applicators, the field distribution in multimode cavities is very complex being a combination of a number of modes supported by the empty cavity within a given frequency range. When a large number of modes are present in a cavity, the electromagnetic fields tend to be more uniform which lead to more uniform heating. The most practical way to increase as much as possible the number of resonant modes is the multiple feeding ports located at specific places on the cavity walls (Datta and Anantheswaran 2001). However, a load insertion into applicator may cause significant change in the mode pattern. Consequently, electromagnetic simulation is an effective tool to optimize the dimension of the multimode resonant cavity applicator and the design of the most suitable location of the feed-port in order to get the desired heat distribution within the manufactured goods.
The precise requirements of the pre-drying process, to uniformly modify the timber in the cross section with minimum possible small checks, leaded to the use of an oversized tunnel applicator and four tapered microwave waveguides placed around the tunnel walls. The size effect of the multimode tunnel applicator on the power distribution inside the timber sample was found through the computer modelling and simulations. The computer design and modelling of the various applicators arrangements and sizes have been performed by means of the commercial modelling software package, CST Microwave Studio. The CST MWS package permits graphical definition of any 3D structure, mesh generation and specification of simulation parameters. The CST MWS electromagnetic simulator is based on the Finite Integration Technique (FIT) which conducts FIT calculations, extracts the desired frequency-domain parameters and displays all the computed fields, and reflection/transmission coefficients.

Modelling was performed for frequency 2.45 GHz, at room temperature of 20ºC and for hardwood timber (*Eucalyptus globulus*), with 105x105 mm dimensions in cross section and moisture content of about 80% and oven-dry density of 0.72g/cm³. For these specifications, the dielectric parameters of wood used in simulation were: $\varepsilon' = 13.2, \tan \delta = 0.27$ for the electric field perpendicular to the grain and $\varepsilon' = 22.4, \tan \delta = 0.32$ for the electric field parallel to the grain (Georgiana Daian 2005).

The tunnel applicator used in the following modelling was a box shaped construction. Since the tunnel width is the most responsive parameter in the applicator system configuration for getting a uniform heat distribution within the load, the various tunnel widths starting from 115x115 mm up to 250x250 mm were used in simulation. The tunnel length was not relevant and it only had to be sufficient to ensure full energy absorption along the sample under processing.

The tunnel applicator loaded with timber is shown in Figure 41. The blue is the air within the metal structure and the brown is the wood positioned in the middle of the tunnel. The background material has been set to be perfect conductive material.
Figure 41: Tunnel applicator with four-source ports tapered irradiators. Tunnel widths a) 115x155mm b) 225x225mm
Four lowered/reduced height irradiators were employed due to the very high intensity microwave radiation have to be involved in the pre-treatment application to achieve higher feed rates and shorter microwave interaction times. Besides the reduction of the interaction zone for the microwave and wood, the taper section functions as a lens concentrating the supplied microwave energy. In a modelling scheme the solver excited the load with a frequency independent electromagnetic power of 1W through a source ports attached to each irradiator.

The irradiators were positioned on the tunnel walls so that the electric field vector to be oriented perpendicular to the Z-direction and, the distance from material to irradiator was set at 10 mm for all applicators. The 10 mm distance was obtained by a computer modelling optimization of the S11 parameters during microwave heating of the wood sample. The main aimed results of the simulation runs were to determine energy distributions within dielectric materials and the maximum power absorbed.

The modification zones for the diverse tunnel sizes were given for comparison in Figure 42. The relative colour scale (lighter to darker colours) is used for visualizing the size of the modification zone for different tunnel applicator widths and the difference in the intensity of microwave radiation. The maximum red colour is assigned to the maximum power loss of each distribution.
Maximum power absorbed by wood

b)

Maximum power absorbed by wood
c)
d) Maximum power absorbed by wood

![Diagram showing energy distribution and intensity inside wood for various applicator sizes]

Maximum power absorbed by wood

Type = Power Loss Density (w/m^2)
Monitor = loss (f=2.45) \( \left( \frac{1}{1.0} \right) + 2 \left( \frac{1.0}{1.0} \right) + \frac{1}{1.0} \)
Maximum 3d = 3782.67 W/m^3 at 95 / 62.5 / 138.54
Frequency = 2.45

e) Maximum power absorbed by wood

![Diagram showing energy distribution and intensity inside wood for various applicator sizes]

Type = Power Loss Density (w/m^2)
Monitor = loss (f=2.45) \( \left( \frac{1}{1.0} \right) + 2 \left( \frac{1.0}{1.0} \right) + \frac{1}{1.0} \)
Maximum 3d = 2772.3 W/m^3 at 25 / 77.5 / 80.8574
Frequency = 2.45

Figure 42: The energy distribution and intensity inside the wood for various tunnel applicator sizes: a) 115x155mm; b) 155x155mm; c) 195x195mm; d) 235x235mm; e) 250x250mm.
As can be seen from the above pictures the size of the modification zone significantly depends on tunnel width. The more uniform distribution along the dielectric sample is given by the biggest size of the tunnel. In addition, the intensity of the absorbed energy is also subject to the tunnel applicator size. The dependency of the peak energy per volume of material intensity on the various tunnel applicator sizes is plotted in Figure 43.

![Figure 43: Dependence of the peak energy intensity on tunnel size](image)

The peak intensity sharply decreases between the tunnel widths 115x115mm\(^2\) – 195x195mm\(^2\). Consequently, the dependence of the absorbed energy intensity on the tunnel size is significant higher toward narrowing the tunnel applicator. Although the larger applicator revealed a more uniform energy distribution along the materials, the low power intensity requires higher exposure to the microwave radiation which may lead to considerable checks. Taking that into account and the fact that the modelling is a static computer simulation procedure, which do not account for the various non-linear processes (i.e. the travelling wood sample on the microwave heating system conveyor) occurring in real experiment, the optimal tunnel width considered for the experimental purposes was 115x115mm.
6.3 Experimental Trials Based on Modelling Results

The experimental trials were performed by using 115x115 tunnel applicator and by applying various supplied power, speeding feed and exposure time. All the tests were done for Blue Gum (Eucalyptus globulus) timber with about 50-80% moisture content and 105x30 mm dimensions in cross section. The 105x30 mm wood dimension was chosen because is one of the most widely used timber in Australia which was consider a good candidate for the MW technology. The cross section pictures of several timber samples, which were modified at different operating conditions, are shown in Figure 44. The microwave modification area was determined by microscope and indicated throughout the pictures.
c)

Figure 44: Microwave modification zone within Blue Gum timber by using the modelled applicator system with 115x115 tunnel applicator and applying various operating conditions: a) low 5+5 kW energy supplied through each radiator and high exposure time 110 sec.; b) higher 10+10 kW energy and lower exposure time 75 sec; c) double energy 20+20 kW and half exposure 40 sec time in respect with the case b

For the case when low energy was applied (5+5 kW), the requested exposure time of the travelling wood dielectric sample on the microwave heating system conveyor was in the order of minutes to get structural modification. This led to the generation of very large splits. When higher energy (10+10 kW) was supplied, the modification took place in an extended area covering nearly whole cross section of the sample. However, big rupture occurred in the middle of the sample along the rays or, there were small cracks but too many. The experiments were further performed by adjusting the operating parameters: the supplied energy was changed (20+20 kW) and the exposure time also modified (40 sec). Under these conditions, the modification area were quite uniform along the cross section with few and very small splits. In addition, much better results were observed in the cases where the timber samples had the annual rings under an angle.
6.4 Conclusions

When using microwave technology, the wood industry solicits a good utilization of the energy together with best quality outputs. These requirements represent the most major challenge in all microwave-wood modification technology design processes. Generally speaking, the optimal utilisation of the energy in conjunction with specific product requirements represented the challenge for this research work as well.

The primarily focus in this chapter was to provide constructive solutions for the wood pre-drying process, such as the microwave equipment configuration to uniformly modify the timber structure in the cross section with minimum possible small checks and without structural defects. The extent of modification of wood by microwaves depends on the treatment time and the power supplied. These requirements provide challenging problems in the design and optimisation of the microwave applicators shape and size which affects the intensity and distribution of energy and hence, the profile of the modification zone.

Starting from technical considerations, several pre-treatment applicator systems of different sizes and configurations were analysed by using computer-aided modelling. The investigation showed the effect of the pre-treatment applicators geometry on the energy distribution and the shape of the treatment zone within dielectric materials.

It was found that the optimal tunnel width for wood pre-drying purposes (wood samples of about 105x30 mm in cross section) is 115x115mm. Although the larger applicators (with dimensions 135x135 mm – 195x195 mm) revealed a more uniform energy distribution along the materials, the intensity of the absorbed energy was showed to be low in these cases. Therefore, no maximum utilisation of the energy would be used and moreover a higher exposure to the microwave radiation would be required which may lead to considerable checks.

By using the 115x115mm tunnel applicator, a quite uniform modification area along the wood sample cross section with only few and very small splits could be achieved for microwave energy of 20+20 kW and 40 seconds exposure time. In addition, it was found that much better results can be obtained in the cases where the timber samples had the annual rings under an angle. Lower microwave energy and higher exposure time generates very large splits or ruptures at different spots within
wood cross section. However, it is recognised that this particular cases may have other practical applications such as wood impregnation.

By establishing the optimum microwave applicator size and parameters of microwave pre-drying wood timber of 105x30 mm, it was achieved a unique task with real practical applications.
CHAPTER 7

REDUCING THE ENERGY REFLECTION FROM APPLICATOR,
FOR MICROWAVE WOOD TREATMENTS

The microwave processing of wood is a widely used as high intensity microwave treatment, which might significantly contribute to the development needs of timber industry. Microwave wood modification requires the application of very intensive microwave energy (up to 30 kW) for very short periods. In wood applications, multimode applicator’s size (“oversize waveguide”) is determined by the wood board size and a reasonable conveyer tunnel production arrangement. The aim of the work presented below is to describe a new and practical way able to improve the functionality of the microwave applicator and to highly reduce the energy reflection to the generators. Firstly, the experimental scale-up applicator for which the reducing energy reflection device was built, it is described. Secondly, the reflection coefficients measured for the empty applicator device and supplied with a moist piece of Eucalyptus globulus timber, is presented. Subsequently, the technical way for reducing the microwave energy reflection for the described applicator configuration is presented by using the computer simulation software, CST Microwave Studio 5.0.1. Finally, the experimental tests of reducing the microwave energy reflection device are presented and has shown that the reflected energy was reduced with more than 50 %.
7.1 Characteristics of the Microwave Processing of Wood as an Energy-Efficient Heating System

In the wood industry, microwave heating might be widely used as a high intensity microwave treatment which creates important changes in wood structure. Also it might significantly contribute to the development of the timber industry, by accelerating wood drying time, relieving of growth stresses, facilitating preservative impregnation and enabling the production of solid wood products.

For example the microwave drying process will reduce dramatically the drying times by making out of date the need for steam conditioning following traditional kiln drying. Microwave conditioning can enable immediate kiln drying of green timber.

It is predicted that microwave irradiation can relieve growth stresses in fast grown plantation hardwoods such as Blue Gums and other Eucalypts. This will enhance significant the wood value. Microwave wood modification requires the application of very intensive microwave energy (up to 30 kW) for very short periods. To achieve such a high intensity and to ensure its subsequent release in the wood it is required to develop new equipment (applicators and radiators) utilizing a range of different frequencies (between 0.4 to 24 GHz) more specific by using industrial available microwave frequencies of 0.922 GHz and 2.45 GHz.

During microwave processing, the spatial distribution of the electric field is inherently non-uniform and has crests at specific locations, which change their positions as the dielectric properties and the microwave absorption of the material change with any increase in temperature. Correspondingly, the strength of the electric field (and thus the heating) is reduced in the core of a wood sample because the microwaves are absorbed non-uniformly due to the different water content in wood cells structure.

In wood applications, multimode “oversized waveguide” applicator’s size is determined by wood board size and reasonable conveyer tunnel production arrangement. The interaction of wood with the microwave field and the changes in the material properties during processing makes the design and the development of the microwave applicators very complex and crucial. Multimode applicator design involves a number of basic parameters including uniformity of heating, required microwave power, applicator size, leakage suppression, reflection, etc.
In an energy-efficient heating system, transfer of energy from generator to workload (input of the device for applying microwave energy to a product) must clearly be achieved with minimum loss. Although a microwave heating system has high transfer efficiency, it is limited by two factors: first, some energy is absorbed in the walls of the transmission waveguide but this represents a very small proportion of the transmitted power and is negligible; and second, a higher proportion of power is reflected from the load back to the generators and this requires special consideration. The reflected energy from the load has to be taken as a given fact by the physics of these processes. To try to avoid it or at least to try to reduce the amount of the reflected energy requires attention in the design of the equipment and careful calculations. This is extremely important, not only by trying to avoid loosing a great amount of money during an inefficient process but also due to the fact that the reflected energy from the wood can damage the magnetron, so, causing big financial loses.

The aim of this work is to describe a new practical way able to improve the efficiency of the applicator by highly reducing the energy reflection to the generators and also to show its performance through the experimental tests and computer simulation and modelling results.

### 7.2 Experimental Setup and Measurements

Solutions proposed included the three-stub tuner (Figure 45) which is ready available on the market and easy to implement. These tuners are waveguide components used to match the load impedance in microwave heating processes. Three-stub tuners can minimize the amount of reflected power, which results in the most efficient coupling of power to the load.
This easy to apply solution was not enough in the case of wood-microwave interaction due to the specific parameters of this process. The solution looked for was the impedance matching between wood and the inserted material in the applicator. This impedance is said to give zero power reflection. That is all of the power is transferred to the load, and none is reflected back to source. Practically due to the dielectric material properties the zero power reflected back to the generator hardly can be achieved but it can be reduced to a level where is not effect on the functionality of the microwave generator.

In order to come up with a practical solution to reduce the energy reflection involved in a particular microwave processing application (which is described below), a good understanding of the reflection parameters was achieved by taking laboratory measurements.

As mentioned in Sub-Chapter 2.2.1 “Reflection and transmission parameters” the reflection parameters Figure 21, 24 and 25 which had to be taken into consideration in realizing the impedance matching design of the equipment.

Because the ideal way of doing a perfect elimination of the reflected energy from the wood to the generators would be the building of the microwave irradiators at the Brewster’s angle (Figure 46) to the microwave applicator, this approach was taken into consideration and analysed.
The Brewster’s angle can be expressed starting with this simple trigonometry as:

$$\theta_1 + \theta_2 = 90'$$

(33)

where $\theta_1$ is the angle of incidence and $\theta_2$ is the angle of refraction.

Using Snell’s law from Chapter 2,

$$n_1 \sin(\theta) = n_2 \sin(\theta_2)$$

(34)

we can calculate the incident angle $\theta_1=\theta_B$ at which no light is reflected:

$$n_1 \sin(\theta_B) = n_2 \sin(90 - \theta_B) = n_2 \cos(\theta_B)$$

(35)

1. Rearranging, we get:

$$\theta_B = \arctan\left( \frac{n_2}{n_1} \right)$$

(36)

During the first stage of this research an on-line available tool of calculating the Brewster’s angle for dielectric materials with particular dielectric properties, in our case wood, it was used. It was found that in order to achieve high power absorption in wood and very low power reflected from wood towards the microwave generators an angle of $\sim11$ degrees has to be built between the microwave irradiators and the microwave
applicators. This angle would provide the microwave applicator with a perfect incident power close to 1 and with reflected energy close to 0 (Figure 47).

The problem consists in the fact that is almost impossible to achieve this goal basically from the engineering and manufacturing point of view.

Figure 47: Brewster’s angle calculation (for zero reflected power from wood)

Further calculations showed that a more suitable angle, the 90 degrees one can be used for this application and a reflection coefficient of 0.32 can be achieved (Figure 48).
Figure 48: Brewster’s angle calculation (reasonable constructive solution)

Following these calculations, the practical testes were conducted and the experimental scale-up applicator for which the reducing energy reflection device was needed was constructed and is presented in Figure 49 below.
The entire applicator device was made up from three specific applicators: box applicator, which provides the mild intensity treatment, tapper applicator and 115x115 mm conveyor applicator. The taper (reduced height) applicator is a modification on the box applicator and is employed for very high intensity microwave radiation. Higher feed rates and shorter microwave interaction times are possible with this applicator. In addition of reducing the zone of interaction for the microwave and wood the taper section functions as a lens, concentrating the supplied microwave energy. The 115x115 mm conveyor is used in conjunction with the box and taper applicators. Installation can be carried out with the vector ε parallel or perpendicular to the wood grain orientation. This gives a total of three configurations (a, b, c1+c2) for this unit, which was graphically suggested by Figure 50.
a) E field parallel to grains

b) E field perpendicular to grains
c1) One applicator (left hand side) E field parallel - One applicator (right hand side) E field perpendicular to grains

Figure 50: Applicator configurations

c2) One applicator (left hand side) E field perpendicular - One applicator (right hand side) E field parallel to grains

Figure 50: Applicator configurations
The reflection coefficients of both empty applicator device and supplied with a piece of wet Eucalyptus globulus timber, were measured by means of a Vector Network Analyser (HP 8720C VNA). It was found that the magnitude of the S11 parameters was of 0.70 and 0.76 respectively. These gave a reflected energy proportion of 32.3% and 42% correspondingly, values which are in accordance with the theoretical ones.

Having confirmed the equipment behaviour under microwave energy, the next step was to move forward to the realisation of impedance matching system.

It is known that the impedance matching is the practice of attempting to make the output impedance of a source equal to the input impedance of the load to which it is ultimately connected, usually in order to maximise the power transfer and minimise reflections from the load (Wikipedia 2006).

7.3 Computer Modelling and Simulation of the Electromagnetic Field

The following step was to design, model and simulate the technical way of reducing the microwave energy reflection for the described applicator configuration.

As mentioned above the solution was to create an impedance matching system in order to reduce the microwave reflection towards to the microwave generator. The Teflon/ceramic materials were considered during this part of the research.

By using the computer simulation software, CST Microwave Studio 5.0.1, the device design accuracy and efficiency was increased exponentially. The practical design consisted in placing a piece of suitable ceramic/plastic (in our experiments Teflon - PTFE), which fits the transversal section of the box applicator, at the applicator end attached to the 115x115mm conveyor-applicator (Figure 51). The main role in reducing the energy reflection is played by the Teflon piece ends shapes: triangular prism towards the generator and parabolic shape towards the conveyor applicator. For such a construction, the computer simulation gives a value of 0.3798 for the magnitude of S11 parameter (gamma-G) in the case in which the conveyor applicator is feed with a piece of Eucalyptus globulus timber of 68% moisture content, which means that only 13.69% from the applied power is reflected.
a) Simulation setup

b) The electric field intensity

Figure 51: CST computer modelling and simulation
Finally, the experimental tests of reducing microwave energy reflection from the applicators were conducted using the new designed device, which gave a "gamma" ($\Gamma$) value of 0.39 for the conveyor applicator supplied with moist wood and 0.12 for an empty applicator.

These results were compared in value with the theoretical and the computer modelled showed that the chosen solution was correct.

7.4 Conclusion

It has to be mentioned that the need for finding a solution able to reduce the microwave reflection towards the microwave generators was arising mainly from the following facts:

- The reflected energy from the load is a given fact resulting from the physics of these processes.
- The easiest available solution of using the three-stub tuner is not enough to deal with the high power microwave processes where a extremely efficient utilisation of the microwave energy is desirable
- The matching impedance solution used around the world in the telecommunication industry can provide a good tool in achieving the desired results by significantly reducing the reflections and improving the transmission of the power to the load.
- The matching impedance solution has to be firstly computer modelled in order to avoid unnecessary money spending on different microwave trials

First the research was focused on the verification of the possibility of having the theoretical Brewster’s angle between the microwave irradiators and the microwave applicator. This was the ideal theoretical solution of avoiding all the reflection to the applicator.

Because of the wood dielectric properties and the timber sizes needed to be treated and structure modified by microwave, this solution proved not to be realizable due to the Brewster’s angle having the value for this case of $\sim$ 11 degrees so extremely hard to practical building it.
Looking deeply on the impedance matching solution, following the computer modelling, the use of plastic/ceramic insertion was chosen. The shape, dimensions and correct dielectric properties for this insertion were carefully chosen so that the energy reflection to be minimized.

Experimental measurements and tests confirmed the theoretical calculations and the modelling results (Table 3).

<table>
<thead>
<tr>
<th>Theoretical value (Γ)</th>
<th>Computer modelling value (Γ)</th>
<th>Practical experiment (Γ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.32</td>
<td>0.37</td>
<td>0.39</td>
</tr>
</tbody>
</table>

Table 3: Gamma values for the microwave applicator having a piece of moist timber inside

To sum up, by using the described technique, it is showed that the reflected energy is reduced by more than 50 % compared with the case of using the microwave applicator device without the special designed Teflon piece. This value provided a good starting point in understanding the shape and the insertion material type to use.

Because, some proportion of the reflected energy from the wood pieces are still reflecting to the generators, it is highly recommended to re-model and design an applicator with special shape able to provide better results. However, it has to be emphasized the importance of this part of the research because any further development involving microwave industrial heating processes will be confronting with the same problems. These problems are arising from the existence in the system of the omnipresent reflection from the wood or any other material under microwave radiation. It was proved by this research that this kind of problems are easily to deal with, by carefully applying the solutions presented here, of course with the need to fulfil the specific requirements for customized applicator shape and dimensions.

This gives a helpful tool to accomplish the proposed microwave wood modification project.
CHAPTER 8

MICROWAVE LEAKAGE SUPPRESSION DEVICE FOR
MICROWAVE CONVEYORIZED LINE FOR WOOD TREATMENT

Safety issues must be seriously considered in the practical implementation of microwave industrial systems with open ports. To preserve the radiation of these open-ended waveguide systems into permissible levels, bandstop microwave filters, water traps, dummy loads and other choke systems are widely used. The problem consists in the fact that for the CRC Wood Innovations wood microwave applications there are no suitable microwave leakage suppression devices available on the market. In this project, the accurate analysis, design and experimental verification procedure of such filters were extensively studied and a solution was delivered. As a result, a new microwave suppression leakage device for continuous wood flow microwave industrial systems was carefully modelled and designed using computer modelling techniques. Following the modelling, it was developed and tested and it is going to play a major role in the future development of the new CRC Wood Technologies’ Microwave Conveyorized Line for Wood Modification.

8.1 Introduction

Nowadays, the microwave energy is used in many applications such as: medicine, radar based systems, mobile communications, and industrial processes. Since microwaves must interact dynamically with the wood material to be processed, the open-ended waveguide systems are usually employed.

In the timber industry, the use of microwave technology for timber processing imposes the application of very intensive microwave energy (up to 300 kW) and hence the need for a continuous flow through a conveyorized line. Therefore, any industrial
microwave heating application necessitates a continuous access aperture into the cavity so that materials may be transported through the cavity by a conveyor. In such systems, the major concern consists in the effect of microwave energy leakage on human tissues. In the microwave wood processing, the design of conveyorized microwave oven with opened ends proportional to the processed timber/log dimensions is still a real problem because it has to comply with the Australian and international occupational safety limits for microwave leakage radiations.

The suppression of microwave energy from the conveyor apertures presents some problems because it is much more complex than a batch-type microwave oven which can be sealed by use of a door. To achieve the proposed aim, so that the intensity of microwave energy permitted to leak from an industrial microwave heating systems to be restricted, the development of a new equipment (applicators) and microwave leakage suppression device was required. The research work undertaken to develop a microwave leakage suppressor for conveyerized line for microwave wood treatment is presented within this chapter.

For modelling purposes and for practical construction of the equipment, the dielectric properties of the Australian wood species wanted to be processed had to be known as these have a significant effect on the choke performance. Therefore, values of the *Eucalyptus globulus* and *Eucalyptus obliqua* dielectric properties were provided by the measurements conducted by our microwave department team and these have been used throughout the modelling described in this chapter.

### 8.2 Preliminary Laboratory Research

Initially, the research work resumed getting preliminary knowledge about the most common microwave absorbing materials. Trials involving different combinations and configurations of well known lossy materials on the waveguide structure surfaces were carried out. Water was also used as an absorbing matter being pumped around microwave transparent conduits. Concluding the tests, it was possible to absorb the residual microwave energy remaining from the dielectric (i.e. wood) heating and to transform it into heat which could be removed by a heat exchanger thereby reducing the temperature of the tunnel and most important absorbing the excess microwave power.
Firstly, the laboratory research was performed using 1 kW microwave generator, a slotted waveguide as microwave energy applicator and a continuous water flow passing through two parallel non-absorbing microwave plastic tubes situated horizontally along the waveguide. The two slots on the waveguide were created such way to maximize the absorption in the two water circulated tubes. (Figure 52).

In this particular case, for an applied incident power of 1 kW, it was found that the water flow absorbs around 99 % percent of the input power.

Encouraged by the results of this very basic experiment, the research was further conducted to the next level using composite microwave absorbing materials available on the microwave specialised market (Table 4). It is known from the microwave shielding industry experience and knowledge that basically these microwave-absorbing materials are well suitable for telecommunication and radar application but custom-made materials can be also used for high power industrial application in combination with other methods of microwave suppression (ARC Technologies, http://www.arc-tech.com/).

The main idea of this approach was to be able to initiate the design of a unique choking system for two open-ends after evaluating the entire available microwave absorbing materials. The aim of the final technical solution was to reduce as much as possible the microwave leakage from system entry and exit points, so that to attain virtually non-detectable levels for both planar and cylindrical heating systems (i.e.
particular tunnel applicators of the CRC for Wood Innovation pilot microwave equipment).

Table 4: Microwave absorbing materials

<table>
<thead>
<tr>
<th>Company</th>
<th>Lossy materials</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Arc Technologies, Inc. U.S.A.</strong></td>
<td>ARC-DD-10017-1; 0.078” Silicone</td>
</tr>
<tr>
<td></td>
<td>ARC-DD-10214-1; 0.030” Silicone</td>
</tr>
<tr>
<td></td>
<td>ARC-ND-12142; 0.018 Thick Nitrile</td>
</tr>
<tr>
<td></td>
<td>ARC-UD-11554; 0.175” Urethane</td>
</tr>
<tr>
<td></td>
<td>ARC-UD-11091; 0.200” Urethane</td>
</tr>
<tr>
<td></td>
<td>ARC-LS-10211</td>
</tr>
<tr>
<td></td>
<td>ARC-LS-10055</td>
</tr>
<tr>
<td><strong>Emerson &amp; Cuming Microwave Products, U.S.A.</strong></td>
<td>ECCOSORB BSR-1/SS-6M: ultra-thin, broadband, high frequency, cavity resonance</td>
</tr>
<tr>
<td></td>
<td>ECCOSORB GDS/SS-6M: thin, broadband, intermediate frequency, cavity resonance, fire retardant</td>
</tr>
<tr>
<td></td>
<td>ECCOSORB MCS/SS-6M: thin, broadband, low frequency, cavity resonance, fire retardant</td>
</tr>
<tr>
<td></td>
<td>ECCOSORB MCS/SS-6M</td>
</tr>
<tr>
<td></td>
<td>ECCOSORB QR-13/SS-3</td>
</tr>
<tr>
<td></td>
<td>ECCOSORB HR-10</td>
</tr>
<tr>
<td></td>
<td>ECCOSORB LS-26/SS-3: economical, broadband, cavity resonance and insertion loss</td>
</tr>
<tr>
<td>--------------</td>
<td>--------------------------------------------------------------------------------</td>
</tr>
<tr>
<td></td>
<td>ECCOSORB SF-10.0/SS-6M</td>
</tr>
</tbody>
</table>

The experiment was conducted using a cylindrical applicator fitted with four cavities. The cavities were coated with absorbing materials and were regarded as microwave ports as well - Figure 53, a). To measure the effect of the absorbing material expressed by the proportion of absorbed power inside the cavities from the transmitted power, the following equipment configuration was used: a microwave power generator attached to a microwave auto tuner through an microwave water-cooled circulator (to prevent the return of the eventual reflected microwaves to generator); a six-port analyser connected to a computer running microwave detection and calculation software; and the cylindrical applicator. The setup configuration of the equipment can be seen in Figure 53, b). During the measurements, the microwave ports were successively connected to the microwave source through the microwave couplers and coaxial cable to analyse and evaluate the effect of different configurations of the electric field.
Figure 53: a) Cylindrical applicator with cavities containing absorbing materials; b) Measurement equipment setup
Several absorbing materials were used during the laboratory trials. In some cases, the measurements led to the total destruction of the materials while for other material types the results were good, ranging from -25 dB to -2 dB. For example, for ARC-DD-10214-1 the measured attenuation (dB) was -2 to -1.5 dB, acceptable for the level of microwave applied power. It was noted that the attenuation depends on the location of the microwave absorbing material sheet inside the cavities: cavity top wall only, bottom wall only, sides only and all interior walls covered. This fact is pointed out in Figure 54 where 1, 2, 3 and 4 represents four different locations of the absorbing material within the cavities (top; bottom; left + right sides; top + bottom + left + right).

![Figure 54: Attenuation obtained using ARC microwave absorbing material](image)

After analysing the microwave absorbing materials it was noticed that the custom-made materials could not be used as a stand-alone microwave suppression solution for the current high power application. The decision was taken after measuring the absorbing materials under high microwave power, 3 to 6 kW, and also having wood
inserted in the microwave applicator so having additional chemicals-wood components together with steam resulted from the wood microwave interaction.

The decision was to continue the research and modelling based on the water trap device but continuing to keep as a supplementary solution the microwave absorbing tunnel fitted with the absorbing materials.

8.3 Computer Simulation/Modelling, Experimental Measurements and Results

Due to the complexity of such devices, many microwave leakage suppression systems were modelled, built and tested.

The first attempt was the design of a leakage suppressor which consisted of a rectangular cavity fitted with four absorbing cavities on each wall having a water circulating system. The inner walls of the main cavity were built from a microwave transparent material.
Following the laboratory test (see experimental setup Figure 56) it was decided that the microwave absorption by the water trap-microwave leakage suppressor device was not suitable to act as a stand-alone microwave suppression device. It was hypothesised that the results were caused by the high voltage inside the cavity which for this particular design produced sparks in excess along the cavity corners.
Figure 56: Experimental setup of the water trap-microwave leakage suppressor

Next, few modelling trials were made by using the computer simulation software CST Microwave Studio 5.0.1, to investigate a reflective device based on the well-known, by the microwave industry professionals, band stop filter, used mostly in the telecommunication industry. - Figure 57.
The reflection/absorption parameters obtained through the computer modelling (Figure 57) demonstrated the effectiveness of the modelled device, especially for 43x86 mm applicator. In Figure 67 a, it is visible the perfect functioning of the band-stop filter for frequency. However, due to the required size of the tunnel applicator (i.e. >150x150 mm) a hybrid suppression system was further considered.
Thus, a reflector device was combined with a resonance-water absorbing device. The main role in absorbing the excess microwave energy was attributed to the resonance-water absorbing equipment (seen in the structure from Figure 59). It was built using five steel cavities. The central cavity, which represents the wood pieces passing section, had 250x250 mm dimensions (as required by the CRC Wood Innovations), and it was projected to be attached immediately after the applicator open-ends. The four 160x160 mm rectangular cavities were placed around the central cavity and fitted with microwave transparent Teflon tubes having continuous water flow. The four cavities were designed to be tuned by internal adjustable plungers. The main principle was to combine the cavity resonance effect with the well-known microwave absorbing properties of the water. Using plungers inserted in the cavities, it was possible to adjust the dimension of the resonant cavity such way that the water absorbing tubes were placed always in the maximum electric field. The water has to be circulated continuously in order to keep under optimal control the microwave leakage and also the increasingly water temperature.

Complementary to this water-absorbing microwave device another piece of equipment was thought to add and extra advantage. A reflective device, based on a modified “magic-tee four port-waveguide coupler”, was modelled and built. The idea behind this equipment (Figure 58) was to try to reflect the microwave radiation, which can escape from the resonance-water absorbing device, back to the applicator as much as possible.
Figure 58: Microwave reflective device

Figure 59: The combined water trap-reflecting device
The computer modelling done prior to the physical execution of the suppression system proved that this complex of microwave water absorbing and reflective device could be of a double way success: firstly, the realisation of a microwave leakage suppression device compliant with Australian and International Standards; and secondly, a much efficient use of the microwave energy by re-applying the energy to the wood pieces.

The electromagnetic simulation and modelling was conducted in the direction of finding the correct interior dimensions for the four small cavities and the right shape and configuration of the device. The modelled structures are displayed in Figure 60 below.
Figure 60: Graphical representation of water trap reflective device - computer modelling: a) view of water absorbing tubes, b) view of absorbing cavities

Once the equipment was built, it was installed and tested in CRC Wood Innovation – Creswick microwave facilities. Supplementary, as an exceptional prevention means against any unexpected microwave accidental leakage, it was used with plurality of thin metal flaps hanging inside the tunnel applicator (Figure 61).
Throughout the tests of the designed microwave leakage suppressor excellent results were recorded (Figure 72). During microwaving a couple of timber pieces, it was observed that not any microwave leakages were recorded at the tunnel ends (as visible on the leakage detector screen in Figure 61) and the operating reflection coefficient had the optimal values for a proper functioning of the magnetrons.

As a further precaution, all equipment’s control systems will be provided with safety interlocks and leakage detectors that shut down power instantaneously in the event of equipment malfunction or misuse.
Figure 62: Generator status during the tests

Incident Power: 3750 W
Reflected Power: 3629 W
96.77% reflected back to wood processing system
8.4 Conclusion

The leakage radiation of any microwave heating application, which necessitates a continuous access aperture into the cavity so that materials may be transported through the cavity by a conveyor, represents a major concern for users and a real challenge for designers.

In practice, various devices (i.e. band-stop microwave filters, water traps, dummy loads and other choke systems) have been customised and used for different microwave applications. However, as their suppression performances depend not only on the tunnel applicator size and geometry but also on the operating conditions of the microwave process (applied energy, batch oven or continuous flow, load, etc.), often, custom-made microwave leakage suppression devices represents a necessity.

The challenge and the novelty of the research work from this chapter consisted in the design and materialisation of a microwave leakage suppressor for a conveyorised line with rectangular opening ends proportional to the processed timber/log dimensions (250x250mm). The final construction represents a genuine engineering solution for novel microwave technologies used to treat timber/logs, being able to reduce the radiations to a level which comply with the Australian and international occupational safety limits, of 50 W/m² at 0.05m, for microwave leakage radiations.

From the investigation of the experimental trials it was found that:

- for standard waveguide applicator and an applied incident power of 1kW, a water flow system absorbed around 99% percent of the input power;
- for larger applicator/opening size (150x150mm), a circulating water configuration (e.g. the water trap-microwave leakage suppressor device) does not suppress satisfactory the microwave leakages;
- custom-made microwave absorbing materials can not be used as a stand-alone microwave suppression solution for the 300 kW power application;
- the well-known band stop filter was indicated by the modelling software to work effectively for large (250x250mm) conveyor tunnels but as hybrid device (the technical solution found was a reflector device combined with a resonance-water absorbing device). For an approx. 3.75 kW applied power, the reflected power back
to the wood pieces under treatment was approx. 3.6 kW so the residual power at the applicator opened end was around 100W, so a reduction of more than 95 %.
CHAPTER 9

CONCLUSION AND RECOMMENDATIONS

In the wood industry, microwave heating might be widely used as a high intensity microwave treatment, which creates important changes in wood structure. Also it might significantly contribute to the development needs of timber industry, by accelerating wood drying time, relieving of growth stresses, facilitating preservative impregnation and enabling the production of solid wood products.

When using microwave technology, the wood industry requires a good utilization of the energy together with best quality outputs. These requirements represent the most major challenge in all microwave-wood modification technology design processes. Generally speaking, the optimal utilisation of the energy in conjunction with specific product requirements represented the challenge for this research work as well.

The challenges and novelty of this development work were:

- establishing technical solutions to uniformly modify the timber structure in the cross section with minimum possible small checks and without structural defects for wood pre-drying process.
- finding a technical solution to reduce the microwave reflection towards the microwave generators
- designing and materialisation of a microwave leakage suppressor for a conveyorised line with rectangular opening ends proportional to the processed timber/log dimensions (250x250 mm).

The primarily focus of this research was to provide genuine constructive solutions for novel microwave technologies used to treat timber/logs. Computer modeling was used as the main tool to design and optimize the microwave systems by conducting realistic process simulations for given dielectric properties, sample size, and desired processing conditions. Besides, the use of computer simulation software played an important role in dramatically reducing the time between the design work and the actual industrial-scale tests. It also helped to reduce the costs associated with the
development of this new equipment by eliminating the need of building up expensive microwave equipment which without a proper design can be useless when used at industrial scale.

Innovative means and equipments were developed and materialised for the microwave wood timber/log treatment technologies. Specific dimensions of pre-drying applicators together with optimum microwave intensity power per volume and loading rate of drying were established in order to uniformly modify the timber structure in the cross section with minimum possible small checks and without structural defects. In addition, the novel idea to insert a dielectric of a particular geometry within the applicator was put forward to reduce the microwave reflection towards the microwave generators. The optimal design of the insertion was established through theoretical calculations, modelling and experiments. Finally, a special and unique microwave leakage suppressor for a conveyorised line with rectangular opening ends proportional to the processed timber/log dimensions (250x250mm) was designed and built.

The physical solutions developed within this research work can serve as valuable equipment for the industrial microwave heating processes of wood. It is expected that once the microwave pilot plant trials of the CRC for Wood Innovation are completed, these developments would be able to be used by a large number of companies from wood industry.

**Key Results**

**A. Technical solutions to uniformly modify the timber structure**

It was found that the optimal tunnel width for wood pre-draying purposes (wood samples of about 105x30mm in cross section) is 115x115mm. Although the larger applicators (135x135mm² – 195x195mm²) revealed a more uniform energy distribution along the materials, the intensity of the absorbed energy was shown to be low in these cases. Therefore, no maximum utilisation of the energy would be used and moreover a higher exposure to the microwave radiation would be required which may lead to considerable fewer checks.
By using the 115x115mm tunnel applicator, a quite uniform modification area along the wood sample cross section with only few and very small splits could be achieved for microwave energy of 20+20 kW at 40 seconds exposure time. In addition, it was found that much better results can be obtained in the cases where the timber samples had the annual rings under an angle. Lower microwave energy and higher exposure time generates very large splits or ruptures at different spots within wood cross section. However, it is recognised that this particular cases may have other practical applications such as wood impregnation.

By establishing the optimum microwave applicator size and parameters of microwave pre-drying wood timber of 105x30 mm, it was achieved a unique task with real practical applications.

B. Reducing the microwave reflection towards the microwave generators

Through experimental measurements, theoretical calculations and modelling, an optimal solution to reduce the microwave reflection towards the microwave generators was found: a piece of Teflon/dielectric ceramic with special geometry inserted into the applicator.

By using the designed Teflon/dielectric insertion configuration, it was shown that the reflected energy was reduced by more than 50% than in the case of using the microwave applicator device without the Teflon/dielectric insertion. This value provided a good starting point in understanding the shape and the insertion material type to use.

Because, some proportion of the reflected energy from the wood pieces are still reflecting to the generators, it is highly recommended to further model and design an applicator with special shape able to provide better results.

C. Microwave leakage suppressor for a conveyorised line

From the investigation of several experimental trials it was found that:

- for standard waveguide applicator and an applied incident power of 1kW, a water flow system may absorb around 99% percent of the input power;
for larger applicator/opening size (150x150mm), a circulating water configuration (e.g. the water trap-microwave leakage suppressor device) working alone does not suppress satisfactory the microwave leakages;

- custom-made microwave absorbing materials can not be used as a standalone microwave suppression solution for the 300 kW power application;

- the well-known band stop filter was indicated by the modelling software to work effectively for large (250x250mm) conveyor tunnels but as hybrid device (the technical solution found was a reflector device combined with a resonance-water absorbing device). For an approx. 3.75 kW applied power, the reflected power back to the wood pieces under treatment was approx. 3.6 kW so the residual power at the applicator opened end was around 100 W, so a reduction of more than 95 %.

**Recommendations for Further Work**

It was mentioned that the primarily focus of this research was to provide genuine constructive solutions for novel microwave technologies used to treat wood timber/log.

The solutions developed during this research are the starting point of the future microwave-wood equipment design and modelling work. Recommendations for further work consist in:

- continuing modelling and design work for developing new microwave applicators suitable for microwave wood bending by this the industry being able to increase the productivity by shortening the long time used for softening of the timber,

- new chambers for microwave drying of the wood shapes obtained from the microwave wood bending processes, chambers to be easily adaptable to various dimensions and quantities of the bent pieces of timber,

- improving the already designed equipment for microwave modification and resin impregnation of railway sleepers,

- microwave accelerated pre-drying of timber used in construction industry and also

- the design and modelling of a new applicator to use for drying of thin sheets of veneer.
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