

Computer Modelling of the Energy Distribution within Wood throughout Microwave Processing

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Abstract: Microwave wood modification and treatment technologies become more and more essential within the wood industry due to their technical and economical advantages. Microwave processing of wood involves many complicated physical phenomena and requires a very careful control of variables (such as intensity of microwave power, loading period, maximum temperature, etc.) in order to reduce structural deformations of the processed wood. To optimise and minimise the project design engineers' work, modelling and simulation of the microwave energy-wood interaction represents an indispensable tool.

This research work has been undertaken with the aim to design and optimise microwave applicators for microwave pre-drying of wood so that to achieve uniform modification of wood in the cross section without generating considerable checks in conjunction with an optimal utilisation of the energy.

A practical and innovative way capable to control the intensity and distribution of the microwave energy and hence to enhance the microwave mod-

ification pattern within wood/timber was theoretically accomplished through 3D electromagnetic simulations and presented within this paper. The theoretical computer simulation values were used as indicative information for the experimental tests. The timber pieces modified by using the new designed microwave wood modification system, demonstrated the benefits of microwave modelling technique and also the effectiveness of the microwave applicator device for the wood modification.

Keyword: Microwave wood modification, 3D electromagnetic simulation, energy distribution.

1 Introduction

High intensity microwave treatment involves many physical phenomena which significantly reduce the traditional processing time and change the features of materials. However, a lack of careful consideration of the intensity of the supplied microwave energy frequently leads to structural deterioration of the dielectric during microwave drying. Cracking, distorting and warping are problems usually caused by the high internal vapour pressure generated by fast heating of the dielectric. As a result, the intensity of microwave power should be carefully selected and the amount of moisture removed during pre-drying should be limited (Metaxas and Meredith, 1993). Likewise, in wood microwave processing, 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

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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. 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, trials and errors are inevitable due to the complexity of the interrelationships among various parameters (i.e. intensity of microwave power, loading period, maximum temperature, etc.). The electromagnetic modelling, simulation, analysis and design tools have become of supreme importance in the cost-effective research and development of the computational electromagnetism (Young and Ruan, 2005; Young et al., 2005; Shu et al., 2005; Ha et al., 2006; Soares et al., 2008) and industrial microwave heating systems. The necessity of the computer-aided modelling is reflected by the challenges which microwave applications confront, and the high costs and time consuming of the experimental methods.

Interest in modelling microwave wood interaction arises from increasing industry understanding of the potential for microwave processing of wood for example in softening of wood for bending of wood components for furniture manufacture (Vinden, Torgovnikov and Hann, NA; Juniper, Ozarska, Burvill, and Bell, NA), use of microwave processing for kiln drying (Vinden and Torgovnikov, 2002; Torgovnikov and Vinden, 2005), preservative treatment and new composite product manufacture (Torgovnikov and Vinden, 2000; Torgovnikov and Vinden, 2002; Przewloka, Hann and Vinden, 2007).

This paper presents the work undertaken to design a practical microwave pre-treatment applicator system with applications in microwave wood modification processes. The effect of various tunnel system's configurations and sizes on the energy distribution and the shape of the treatment zone within wood material has been investigated. The computer-aided modelling was used as the

principal tool to examine the energy distribution in the wood specimen and the maximum power loss behaviour as the size of the tunnel applicator varies. Initially, the paper presents the 3D electromagnetic simulations of the energy distribution within a piece of wood by using diverse dimensions for the microwave tunnel and a specific configuration of four tapered radiators. Subsequently, based on the simulation results and the physical and practical facts observed, the optimal tunnel width was determined and considered for experimental use. Finally, optimisation was further performed by carrying out experimental trials.

2 Simulation and optimization of the energy distribution within in wood, generated by different size applicators

In microwave heating applications for long or bulky products, 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 - 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 leading to a more uniform heating. The most practical way to maximise the number of resonant modes inside the cavity applicators 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 this context, the optimisation relates to the generation of a desired heat distribution within the processed material.

Based on the above considerations and the precise requirements of the pre-drying process to uniformly modify the timber in the cross section with minimal small checks, an oversized tunnel applicator and four tapered microwave waveguides placed around the tunnel walls was investigated. The size and design effect of the multimode tun-

nel applicator on the power distribution inside the timber sample was studied by computer modelling and simulations (i.e. CST Microwave Studio software package – CST MWS).

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.

The tunnel applicator was graphically designed as a box shaped construction with a certain length and variable widths using the CST MWS. The tunnel width is the most responsive parameter in the applicator system configuration for getting a uniform heat distribution within the load. Thus, various widths starting from 115x115mm up to 250x250mm were considered. Tunnel length has no microwave modification relevance but had to be sufficient long to ensure full energy absorption along the sample under processing.

The four lowered/reduced height irradiators were considered for two main reasons: to uniformly modify the timber cross section and to achieve higher feed rates and shorter microwave interaction times as very high intensity microwave radiation has to be applied in the pre-treatment application. The taper section of the irradiators operates like a lens, concentrating the supplied microwave energy. In modelling, the irradiators were positioned on the tunnel walls so that the electric field vector to be oriented perpendicular to the Z-direction.

The 3D graphical representation of the tunnel applicator loaded with a timber piece is shown in Fig. 1. The lighter colour represents the air inside the metal structure whereas the darker colour represents the wood piece placed in the middle of the tunnel. The background material has been set to be a perfect conductive material.

The critical parameters simulated in the modelling sessions were: frequency 2.45 GHz, room temperature (i.e. 20°), loaded material

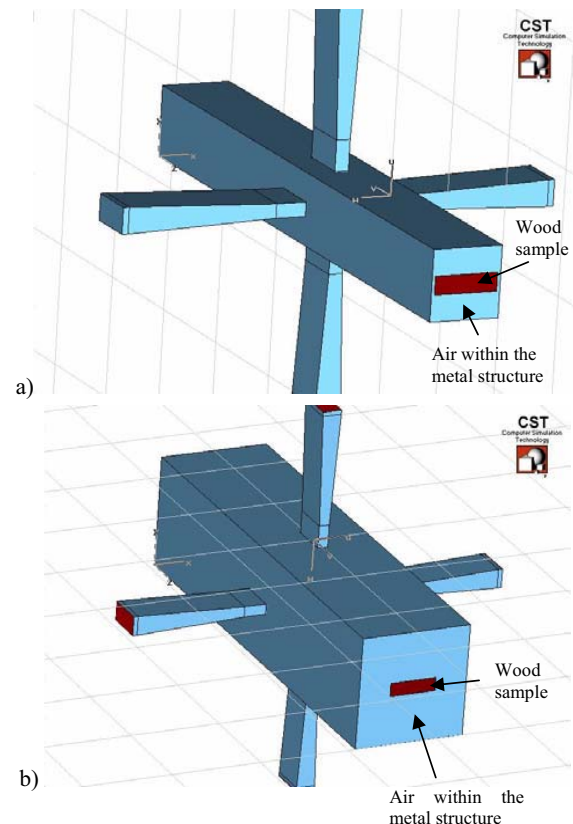


Figure 1: Tunnel applicator with four-source ports tapered irradiators. Tunnel widths a) 115x155mm b) 225x225mm

- hardwood timber (*Eucalyptus globulus*), with 105x30mm dimensions in cross section, moisture content of about 80% and oven-dry density of 0.72g/cm³. For these specifications, the dielectric parameters of the wood were estimated as follows: $\epsilon' = 13.2$, $\tan \delta = 0.27$ for the electric field perpendicular to the grain and $\epsilon' = 22.4$, $\tan \delta = 0.32$ for the electric field parallel to the grain (Daian, Taube, Birnboim, Daian, and Shramkov, 2006).

The reflection parameters (i.e. S11, S22) were optimised by adjusting the distance from the wood material and the irradiators. The computer simulation showed that minimum reflection is obtained when the irradiators are 10mm away from the load. In all subsequent simulations for determining the energy distributions within dielectric materials and the maximum power absorbed, the distance between the wood piece and irradiators

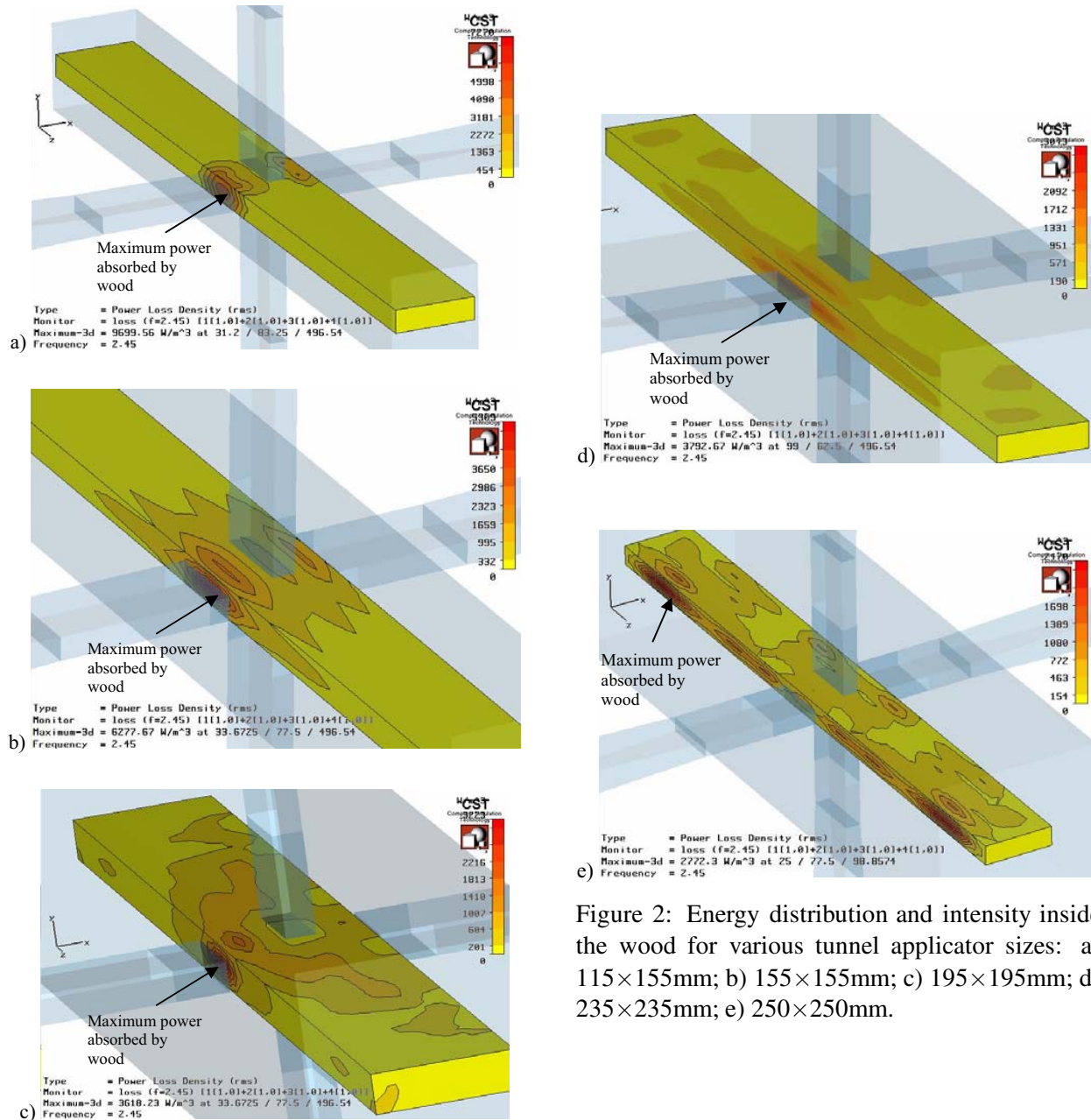


Figure 2: Energy distribution and intensity inside the wood for various tunnel applicator sizes: a) 115×155mm; b) 155×155mm; c) 195×195mm; d) 235×235mm; e) 250×250mm.

was set to 10mm and the only variable was the tunnel applicator size.

The microwave modification zones, obtained across the wood sample as a result of changing the tunnel aperture dimensions, are given in Fig. 2. The relative colour scale, from lighter to darker colour tones, is indicative of the modification zone size for different tunnel applicator widths. It also highlights the difference in the microwave radiation intensity. The maximum dark

colour is assigned to the maximum power loss of each distribution.

Fig. 2 shows the size of the modification zone significantly depends on tunnel width: the bigger the tunnel width, more uniform distribution along the dielectric sample. In addition, the intensity of the absorbed energy is subject to the tunnel applicator size. The dependency of the peak energy intensity per volume of material on the various tunnel applicator sizes is plotted in Figure 3.

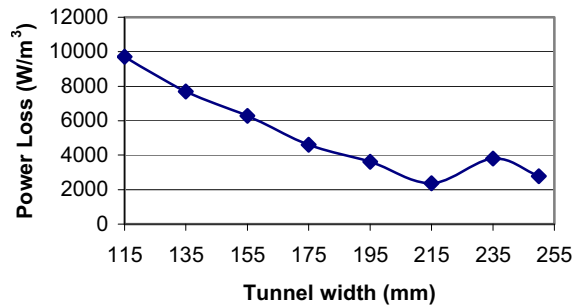


Figure 3: Dependence of the peak energy intensity on tunnel size.

The intensity of the maximum power absorbed by wood sharply decreases as the tunnel width increases from 115x115mm to 195x195mm. Consequently, it was concluded that the maximum absorption of the energy occurs as the tunnel applicator narrows.

Although the larger applicator revealed a more uniform energy distribution along the materials, the low power intensity requires higher exposure time to the microwave radiation which may lead to considerable checks in the wood. Taking into account that the modelling is a static computer simulation procedure, which limits the effects of the various non-linear processes (i.e. the travelling wood sample on the microwave heating system conveyor) occurring in the real applications, the optimal tunnel width considered for the experimental trials was 115x115mm.

3 Experimental trials based on modeling results

The experimental trials were performed by using the modelled applicator system with the 115x115 tunnel applicator and application of various supplied powers, speeding feeds and exposure times. Tests were carried out upon Blue Gum (*Eucalyptus globulus*) timber with a moisture content of 50-80% and 105x30mm dimensions in the cross section. The selected timber cross section is recognised as being the most commonly used in the Australian timber-based sector.

The cross section pictures of several timber samples modified at different operating conditions of:

- 5+5kW (supplied by two generators) through each irradiator, and 110sec exposure time,
- 10+10kW (supplied by two generators) through each irradiator, and 75sec exposure time,
- 20+20kW (supplied by two generators) through each irradiator and 40sec exposure time,

are shown in Fig. 4. The microwave modification area was determined by microscopic analysis and is highlighted.

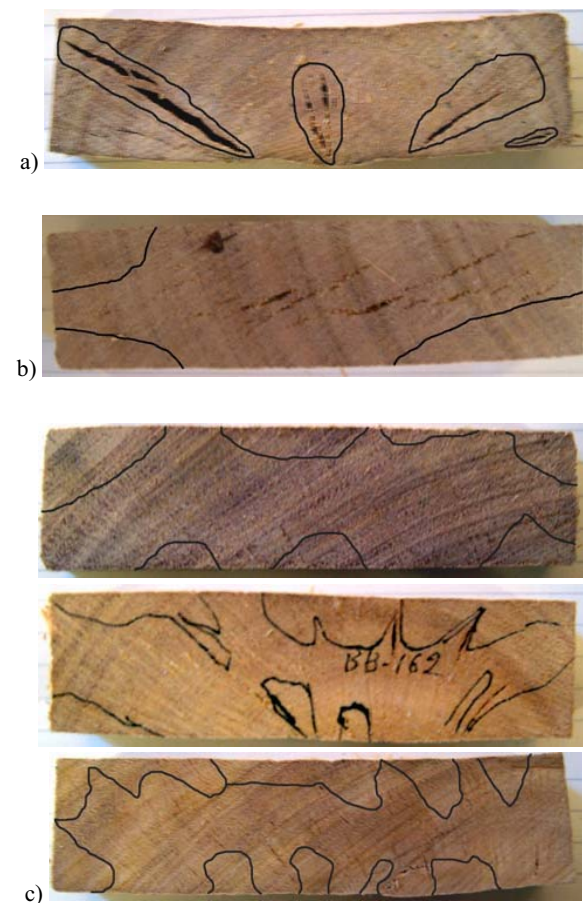


Figure 4: Microwave modification zone inside Blue Gum timber samples. a) 5+5kW applied energy and high exposure time 110sec.; b) 10+10kW applied energy and lower exposure time 75sec; c) 20+20kW applied energy and half exposure 40sec time in respect with case b.

When low energy (i.e. 5+5kW) was applied

through the four irradiators, the wood sample required a long traveling and exposure time (i.e. minutes) through the conveyerised microwave applicator system in order to be heated and achieve structural modification. This led to the generation of very large splits. When higher energy (i.e. 10+10kW) was supplied, the modification took place on an extended area, covering nearly the whole cross section of the sample. However, big ruptures occurred in the middle of the sample along the rays or sometimes many small cracks were developed. The experiments were further performed. Adjusting the operating parameters by doubling the supplied energy (to 20+20kW) and halving exposure time (to 40sec) produced modification areas that were quite uniform along the wood samples' cross section with few and very small splits. In addition, much better results were observed in the cases where the timber samples had been quarter-sawn.

4 Conclusions

The wood industry demands optimisation of energy use and best quality outputs. These requirements represent major challenges in all microwave-wood modification technology design processes. The optimal utilisation of the energy in conjunction with specific product requirements also represented the challenges of this research work.

The primary focus of this study was to provide constructive solutions for the wood pre-drying process. The microwave equipment configuration had to be designed to uniformly modify the timber structure in the cross section with minimum and small checks, and without structural defects. The extent to which microwave modification of wood occurs depends on the treatment time and the supplied power.

Several pre-treatment applicator systems with different dimensions and configurations were analysed using computer-aided modelling. The investigation revealed the effect of the pre-treatment applicator's geometry on the energy distribution within the wood samples. It was found that the optimal tunnel applicator width for the microwave pre-drying of wood samples of about

105×30mm in cross section is 115×115mm. Although larger applicators with dimensions between 135×135mm and 195×195mm revealed a more uniform energy distribution along the loaded material, the intensity of the absorbed energy was lower. Therefore, no maximum utilisation of the energy would be used in the latter cases and a higher exposure time to the microwave radiation would be required. This could lead to extensive checking.

Experimental trials were carried out using the customised 115x115mm tunnel applicator. A uniform modification area along the wood sample cross section was achieved for a microwave energy supply of 20+20kW (i.e. two generators were in use) and 40 seconds exposure time. The modification area was characterised by a few very small splits. In addition, it was found that much better results could be obtained when the timber samples were quarter-sawn. Lower microwave energy and higher exposure time generated very large splits or ruptures at different locations inside wood. It is recognised that low microwave energy and high exposure times may have other practical applications such as wood impregnation.

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