COMPUTATIONAL ANALYSIS OF HEAT AND MASS TRANSFER DURING MICROWAVE DRYING OF TIMBER

by

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The need for improvement in engineering design and process optimization for microwave drying of wood has stimulated the development of computer simulation techniques to predict temperature and moisture history and distribution wood sample.
A 3-D comprehensive heat and mass transfer model was developed to simulate the free liquid, vapor, and bound water movement including consideration of internal heat generation in microwave drying of yellow poplar specimens. The model was solved using the finite element analysis with FEMLAB software. The model predictions compared favorably with predicted and experimental solutions. The effect of changes of the most important parameters on the predictions of the model is also presented. The results showed that the variations of irradiation time, microwave power level and sample thickness played an important role in overall drying kinetics.

Key words: *microwave drying, wood, heat and mass transfer, porous media, modelling*

Introduction

Drying is the most energy-intensive and time-consuming component of the lumber manufacturing process. The most of the technic used to dry wood is the conventional and vent kilns, where hot and dry air is used. This technic is simple and inexpensive. However, the quality of the final product is often low and the drying time is very long. Drying wood by microwave energy is not very common, but could be a complement to conventional air-circulation drying due to the possibility to dry wood much faster than conventional drying with preserved quality. Microwave drying is characterised by rapid heating and the development of high pressure and temperature inside the solid which leads to rapid moisture transport and significant potential time savings. Most manufactured solids are dried at least once in their manufacture, making drying one of the most important unit operations in the process industries. To establish an effective drying model is an important part in the fundamental study of wood drying and is also a precondition in realizing fully automatic drying control, improving drying quality, reducing energy consumption, and shortening drying time. In conventional heating processes, energy is transferred to the material by convection, conduction

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and radiation phenomena through the external materials surface, in presence of thermal gradients. However, microwave energy is transferred to the wood material through molecular interactions with electromagnetic field via conversions of electromagnetic energy into thermal energy [1-3].

Understanding the mechanism of moisture evaporation and movement during drying of wood is particularly important to correctly interpret moisture transport phenomena. Mathematical modeling is a useful way to describe heat and mass transport during wood drying. Several theoretical models have been proposed in the study of microwave drying process. The process of wood drying involves simultaneous transport of heat and mass through the wood [4]. Cloutier *et al.* [5] elaborated a finite element model for isothermal drying and water transfer model to describe the characteristics of the process of wood drying based on water potential concept. Comprehensive models of heat and mass transfer during microwave drying can be divided into two categories: Luikov-type model [6], based on the theory of non-equilibrium thermodynamics and those based on mechanistic models, [7]. Antti *et al.* [8-10] conducted extensive studies on microwave drying of ash, beech, oak, pine, and spruce lumbers. Due to potential internal pressure built-up and failures, 40 they concluded that the microwave drying method was most suitable for thin pieces of lumber, veneer, or strands. Perre *et al.* [11] combined a 2-D transfer code with a 3-D multiphase computational scheme, obtained the overall behaviour of combined microwave and convective drying of heartwood spruce remarkably well and predicted the occurrence of thermal runaway within the material.

Cividini and Travan [12] and Seyfarth *et al.* [13] proposed the application of a combination of vacuum and microwaves. This technology shortens drying time to minutes. Drying temperature can be very low, between 30 °C and 40 °C, thus avoiding thermal degrade and chemical reactions causing discoloration of wood.

A formulation of a dynamic, kiln-wide drying model was described by Sun *et al.* [14], and the model solves the unsteady-state mass, momentum and energy balance equations for both the airflow and the wood boards. Koumoutsakos *et al.* [15] developed a 1-D mathematical model to describe the transport phenomena during continuous radio-frequency-vacuum drying of thick lumber by assuming no capillary flow at moisture content above fiber saturation point. Li *et al.* [16] studied the mechanism of moisture and heat transfer within wood during microwave-vacuum drying and a 1-D mathematical model to describe the process of wood microwave-vacuum drying was established and verified by numerous experiments.

Moschler and Hanson [17] developed a prototype microwave-based moisture sensor system suitable for the kiln drying of hardwood lumber. Hukka [18] studied a 2-D model for the stress analysis of drying wood. Younsi *et al.* [19-21] considered heat treatment of wood by solving diffusion equation in wood and turbulent Navier-Stokes equation in the fluid field for Thermo-wood technology. The experimental results and the model predictions were found to be in good agreement. A parametric study was presented.

The advantage of this simple model, Luikov model [6], is it contains less unknown constants, or in two words, we need less experimental work to determine the constants of the model, compared to multiphase model [22].

One way to understand and explain the physical processes in the interaction between wood and microwaves, which could be the basis for controlling and scheduling the heating, with or without drying, or for microwave scanning, is to make simulation models. The numerical modelling of microwave-assisted drying processes is a complex task that requires the accurate knowledge of several thermo-physical, dielectric, and boundary condition parameters that appear in the mathematical formulation.

In order to improve the drying process and reduce energy utilization, it is desired to develop a 3-D mathematical model to evaluate relative performance of microwave drying of wood. The overall goal of this study was to provide insight in understanding the characteristics of microwave drying of wood. A parametric study was carried out.

Mathematical formulation and modelling

Drying is usually described as a coupled process of heat and mass transfer. In this study, The Luikov model with Lambert's law for power absorption in 3-D was used to simulate the heat and mass transfer in a porous sample (wood) during drying process. The sample is initially at uniform temperature and uniform moisture content (T_0, M_0), fig. 1.

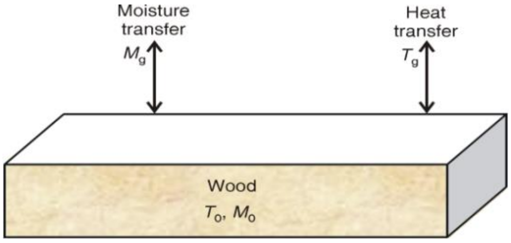

Figure 1. Schematic of the physical model

The following assumptions were made in order to simplify the model:

- the initial moisture and temperature distribution in wood is uniform,
- the solid and gas are continuous, as is the liquid phase above fiber saturation point (FSP),
- moisture transport is dominated by bound water diffusion and vapor bulk flow below FSP and capillary flow and vapor bulk flow above FSP,
- the gas phase is water vapor, which behaves as an ideal gas,
- the bound water has physical properties similar to those of free water, and
- gravity is negligible.

Based on previous assumptions, the equations describing 3-D heat and moisture transfer in wood during microwave drying process are given:

- heat transfer

$$\rho\, c_q \frac{\partial T}{\partial t} = \vec{\nabla}\left[\underbrace{\left(k_\mathrm{q} + \frac{\chi\,\lambda\,k_\mathrm{m}\,\delta}{c_\mathrm{m}}\right)}_{\textit{Fourrier}\ \text{law}}\vec{\nabla} T + \underbrace{\chi\,\lambda\,k_\mathrm{m}}_{\substack{\textit{Non-isothermal}\\ \textit{diffusion}\ \text{law}}}\vec{\nabla} U + Q\right] \tag{1}$$

- moisture transfer

$$\rho\, c_\mathrm{m} \frac{\partial U}{\partial t} = \vec{\nabla}\left[\underbrace{\left(\frac{k_\mathrm{m}\,\delta}{c_\mathrm{m}}\right)}_{\textit{Soret effect}}\vec{\nabla} T + \underbrace{k_\mathrm{m}}_{\textit{Fick's}\ \text{Law}}\vec{\nabla} U\right] \tag{2}$$

The first term on the right hand side of eq. (1) is the heat transfer by conduction *Fourier Law*; a term is added for the component of heat transfer due to phase change. The heat transfer takes place due to temperature gradient. However, in the case of coupled heat and mass transfer, it also takes place due to moisture gradient. However, this is considered insignificant for porous bodies. The second term is the component of non-isothermal diffusion. The most obvious direct effect of microwave heating is embodied in the source term Q accounting for source of heat generated by microwave power dissipation (the third term). When $Q = 0$, this model reduces to the conventional convective drying.

The first term on the right hand side of eq. (2) represents the mass transfer taking place because of the gradient in temperature, *Soret effect* and the second term is the component of mass transfer due to the gradient in moisture concentration, *Fick Law*.

The initial and boundary conditions are given:

$$-k_{\mathrm{q}}\frac{\partial T}{\partial n}=h_{\mathrm{q}}(T-T_{\mathrm{g}})+(1-\chi)\,\lambda\,h_{\mathrm{m}}(U-U_{\mathrm{g}})+\sigma\varepsilon(T^{4}-T_{\mathrm{g}}^{4}) \tag{3}$$

$$-k_{\mathrm{m}}\frac{\partial U}{\partial n}=\left(\frac{k_{\mathrm{m}}\,\delta}{c_{\mathrm{m}}}\right)\frac{\partial T}{\partial n}+h_{\mathrm{m}}(U-U_{\mathrm{g}}) \tag{4}$$

where n is the spatial direction x- (longitudinal), y- (radial), and z- (transversal).

$$T = T_0 \qquad \text{at} \qquad t = 0 \tag{5}$$

$$U = U_0 \qquad \text{at} \qquad t = 0 \tag{6}$$

where T is the temperature, U – the moisture potential, Q – the power density, t – the time, ρ – the dry body density, c_{q} – the heat capacity, k_{q} – the thermal conductivity, k_{m} – the moisture conductivity, ε – the ratio of vapour diffusion coefficient to total moisture diffusion, λ – the latent heat, δ – the thermal gradient coefficient, U_{g} – the gas moisture potential, T_{a} – the ambient temperature, h_{q} – the convective heat transfer coefficient, and h_{m} – the convective mass transfer coefficient.

The moisture potential, U, is related to the moisture content, C, by:

$$M = c_m\, U \tag{7}$$

where c_m is a constant.

The previous eqs. (1) and (2) are non-linear with boundary conditions given by, eqs. (3) and (4). Therefore, the equations have to be solved numerically.

Equations (1) and (2) can be written in the following generalized form:

$$A_{11}\frac{\partial T}{\partial t}+A_{12}\frac{\partial U}{\partial t}=\vec{\nabla}\left[K_{11}\vec{\nabla}T+K_{12}\vec{\nabla}U\right]+Q \tag{8}$$

$$A_{21}\frac{\partial T}{\partial t}+A_{22}\frac{\partial U}{\partial t}=\vec{\nabla}\left[K_{21}\vec{\nabla}T+K_{22}\vec{\nabla}U\right] \tag{9}$$

where the coefficients A_{ij} and K_{ij} are:

$$A_{11}=\rho\,c_q, \qquad A_{12}=0, \qquad A_{21}=0, \tag{10}$$

$$K_{11}=\left(k_q+\frac{\varepsilon\,\lambda\,k_{\mathrm{m}}\,\delta}{c_{\mathrm{m}}}\right), \qquad K_{12}=\varepsilon\,\lambda\,k_{\mathrm{m}}, \qquad K_{21}=\left(\frac{k_{\mathrm{m}}\,\delta}{c_{\mathrm{m}}}\right), \qquad K_{22}=k_{\mathrm{m}} \tag{11}$$

The equations are solved with FEMLAB software [23] which operates in the MATLAB environment. It uses the finite element technique. A grid independent solution is ensured by comparing the result of different grid meshes, fig. 2. Simulations were carried out using three grids with Grid1-3182, Grid2-6580, and Grid3-8394 elements. The predictions did not vary significantly. The rest of the simulations were carried out with a grid of 6580 elements, fig. 3.

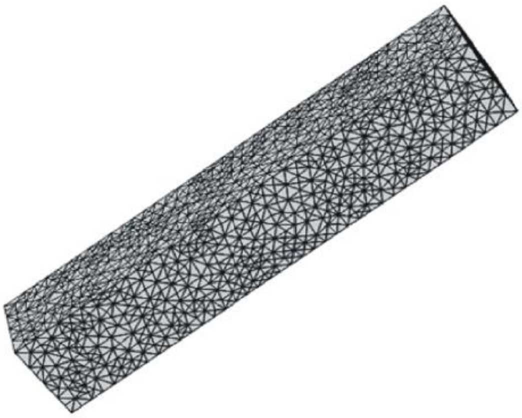

Figure 2. Schematic of the mesh

Thermo-physical properties of wood

The accuracy of this model depends on the accuracy of the thermo-physical properties of wood. The density, ρ, specific gravity, G_m, specific heat, c_p, and thermal conductivities (k_{qx}, k_{qy}, k_{qz}) of moist wood were calculated using relations proposed by Simpson and Tenwold [24] and Siau [25]:

$$\rho = 1000 G_\mathrm{m} (1 + M/100) \tag{12}$$

The heat capacity and thermal conductivity of moist wood are functions of both moisture content and temperature:

$$c_p = \frac{c_{p0} + 0.01\, c_{p\mathrm{w}} M}{1 + 0.01 M} + A_c \tag{13}$$

where M [%] is the moisture content, $c_{p\mathrm{w}}$ – the heat capacity of water, c_{p0} – the heat capacity of dry wood, and A_c – a parameter which is a function of moisture content and temperature.

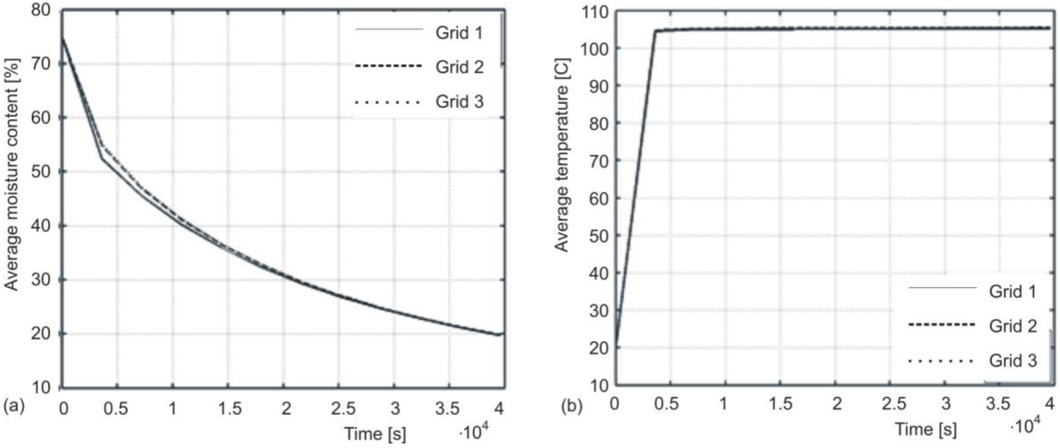

Figure 3. Grid independence test; (a) average moisture content and (b) temperature evolutions for different grid size (T_0 = 20 °C, M_0 = 75%, Q = 1.0·10^5 W/m^3)

The c_{p0} and A_c are given:

$$c_{p0} = 0.1031 + 0.003867\, T \tag{14}$$

$$A_c = M(-0.06191 + 2.36 \cdot 10^{-4} T - 1.33 \cdot 10^{-4} M) \tag{15}$$

The thermal conductivity of wood in longitudinal direction is approximately two times higher than that in transversal or radial directions as reported in the literature [25]. The thermal conductivities in different directions are:

$$k_{qz} = k_{qy} = G_\mathrm{m}(0.1941 + 0.004064 M) + 0.01864 \left(k_{qx} = 2k_{qy} = 2k_{qz} \right) \tag{16}$$

Heat of vaporization data from steam tables was fitted to a polynomial as a function of temperature and given:

$$\lambda = 2.792 \cdot 10^6 - 160T - 3.43T^2 \tag{17}$$

Table 1. Parameters used in the simulations

Property	Expression	Ref.
c_{pw} [Jkg^{-1}K]	4185	[25]
C_m [= kg$_{moisture}$/kg. °M]	0.01	[25]
D [m^{2}s^{-1}]	$D=\dfrac{9.2\cdot10^{-9}T_K^{2.5}}{T_K+245.18}$	[25]
G_m	0.40	[25]
χ	0.3	[25]
ε	0.85	
δ [= kg$_{moisture}$/kgK]	0.025	[25]
k_m [= kg$_{moisture}$/ms°M]	$1.8\cdot10^{-8}$	[25]
M_0 [%]	75%	
T_0 [K]	280-298	
σ [Wm^{-2}K^{-4}]	5.67e–8	

The other transport, physical properties and flow conditions used are summarized in tab. 1.

The validation of the Luikov's model was already carried out by comparing the predictions of the model with the experimental results obtained during the high temperature treatment of Jack Pine (*Pinus banksiana Lamb*) wood. More detailed information on the validation is given elsewhere [19-21]. We have also tried to validate the model with the experimental and numerical results obtained from Jia and Afzal [26] for 2-D microwave drying of white oak. The comparison shows good agreement (fig. 4).

Results and discussion

Predicted microwave of yellow poplar was carried out. The dimensions of the samples were 20 cm (longitudinal) × 3.5 cm (radial) × 3.5 cm (transversal). The thermo-physical properties and the treatment conditions used in the simulations are listed in tab. 1. Initially the board was assumed to be at the ambient temperature of 20 ℃ and average moisture content 75%. In such problem, it is important to know how the temperature and moisture distribution change with time.

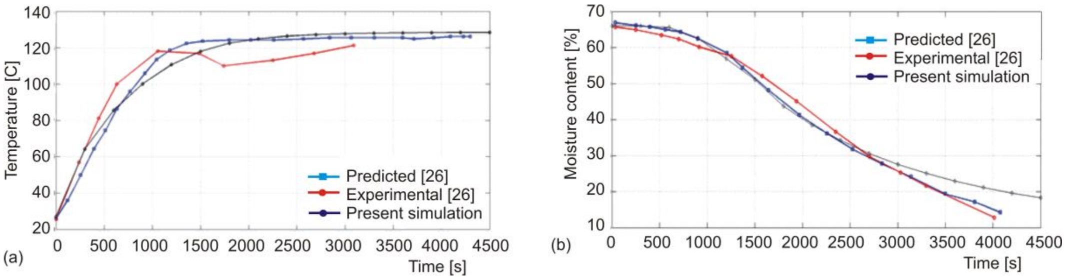

Figure 4. Comparison of predicted and experimental temperature evolution and moisture content evolution during 2-D microwave drying of white oak (Q = 2.2·10^5 W/m^3)[26]

This information can be used to adjust the treatment parameters and, consequently, to control the quality of final product more effectively. In the model, the temperature and moisture distributions of the wood were calculated at each time step. The average moisture content of the material at any time step was determined by averaging the calculated moisture distribution in the sample. In order to investigate the effect of heating power, a number of simulations were carried out. The initial MC of samples was about 75%. Figure 5 illustrates the predicted temperature and average moisture as a function of time for various heating power. As the heating power decreases, it takes longer to reach a given temperature and to reduce the moisture content to minimum. It can be observed from the figures that, at any given time, the higher the microwave power is, the higher the wood temperature is and the lower the average moisture content of the wood is. This is expected since higher microwave power results in larger exchange potentials which favours the evaporation of water from wood. By increasing power radiation, the moisture within wood can absorb more energy and result in higher temperature and evaporation rate.

In addition, moisture within wood can boil and change into water vapour during process.

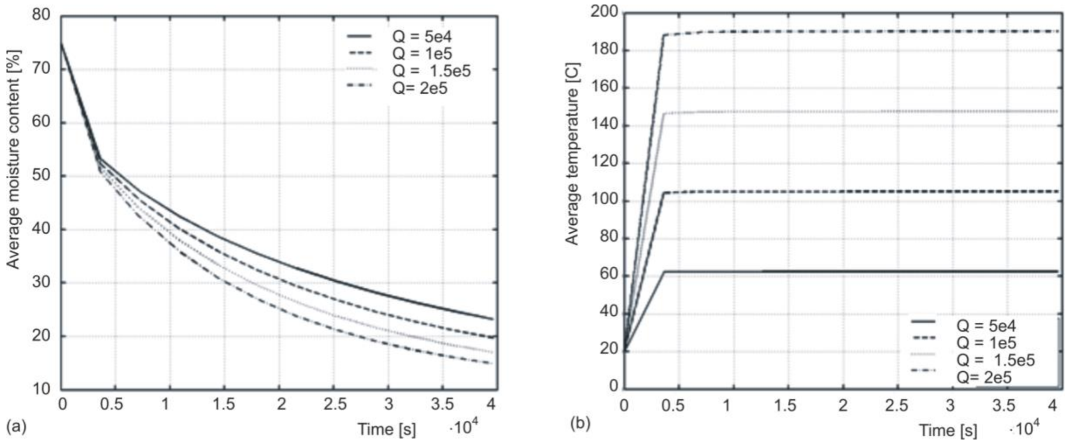

Figure 5. Time evolution of (a) average moisture content and (b) temperature profiles for different microwave power (T_0 = 20 °C, M_0 = 75%)

Figure 6 illustrates the distribution of temperature and the moisture content inside the sample for several times. It is clearly seen that all the profiles are symmetrical as expected since all external surfaces of the sample are subjected to the same boundary conditions. Since wood is anisotropic, it is better to consider this behaviour to verify if the profiles remain symmetric or not. The moisture gradient decreases as the distance from the heat exposed surfaces increases, *i. e.*, the closer to the surface of the board, the lower the moisture content will be.

Using the model, the average temperatures and moisture content distributions at different times can be predicted for any size wood sample. Simulations were carried out for three different sample sizes. For these simulations, the width of the sample was kept constant (0.035 m). The geometrical ratio (length/thickness) of the samples was taken as 1, 5.7, and 14.3.

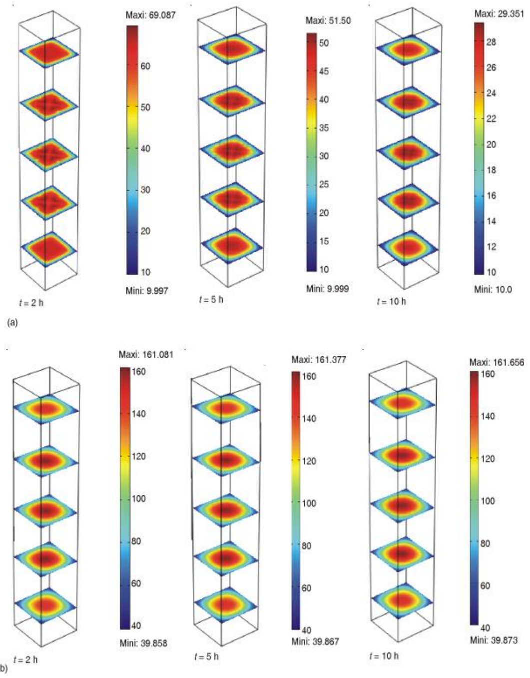

Figure 6. Spatial profiles of (a) moisture content and (b) temperature during microwave drying (T_0 = 20 °C, M_0 = 75%, Q = 1.0·10^5 W/m^3)

Figure 7 compares the temperatures and moisture content of the samples for different sample sizes. During the microwave drying, the internal heat will be generated in the wood sample, internal moisture move easily to surface and the dehydration rate will increase. However, increase in the thickness will increase the energy required for transfer. Probably, the thicker sample increases the wood temperature gradient (because of volumetric heating) and thus affects the internal gaseous pressure, resulted in more boiling and more bubbling of the samples. The thick sample used the more energy than the thin sample. This reflects the low rehydration rate and long drying time for thick samples.

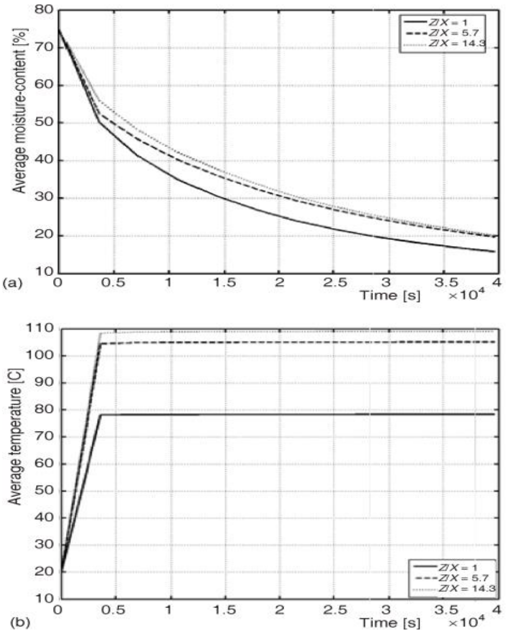

Figure 7. Time evolution of average (a) moisture content and (b) temperature profiles for different size of the sample (T_0 = 20 °C, M_0 = 75%, Q = 1.0·10^5 W/m^3)

Conclusions

A comprehensive 3-D heat and mass transfer computational model has been used to achieve a better understanding of the microwave drying of wood and to determine its influence on several parameters that control the process.

This study is carried out by solving 3-D Navier-Stokes equations for the fluid field and Luikov model for the porous solid.

The Femlab software was used to solve the coupled system of partial differential equations. This model can be an important tool for the design of new furnaces, for the analysis of problems encountered in existing furnaces, and optimization of their operation. Computational methods can considerably reduce costly experimental time and increase the understanding of microwave wood drying. Also, it is interesting to take into account shrinkage/Swelling in the model as well as the anisotropy of wood to analyses the behavior of temperature and moisture content inside wood. Experimental apparatus is in progress to validate the numerical predictions.

Nomenclature

c_m	– moisture capacity, [kg$_\mathrm{moisture}$ kg^{-1} M^{-1}]
c_q	– heat capacity, [Jkg^{-1}K^{-1}]
D	– diffusion coefficient, [m^2 s^{-1}]
G_m	– specific gravity
h_q	– convective heat transfer coefficient, [Wm^{-2}K^{-1}]
h_m	– convective mass transfer coefficient, [= kg$_\mathrm{moisture}$m^{-2}s^{-1}M]
k_q	– thermal conductivity, [W/m^{-1}K^{-1}]
k_m	– moisture conductivity, [= kg$_\mathrm{moisture}$m^{-1} s^{-1} M^{-1}]
M	– moisture content, [= kg$_\mathrm{moisture}$/kg$_\mathrm{drybody}$]
n	– normal
Q	– power density, [Wm^{-3}]
T	– temperature, [K]
t	– time, [s]
U	– moisture potential, [M]
W	– weight, [kg]

Greek symbols

δ	– thermal gradient coefficient, [= kg$_\mathrm{moisture}$/kgK]
ε	– wood emissivity
λ	– latent heat, [Jkg^{-1}]
ρ	– dry body density, [kgm^{-3}]
σ	– Boltzman constant, [Wm^{-2}K^{-4}]
χ	– ratio of vapour diffusion coefficient to coefficient of total moisture diffusion

Subscripts

a	– ambient
g	– gas
m	– moisture
w	– water
0	– initial

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