TIME DOMAIN CHARACTERIZATION OF COUPLED ELECTROMAGNETIC/THERMAL PHENOMENA FOR MATERIAL PROCESSING

M. Righi, J. L. Herring*, and W. J. R. Hoefer

NSERC/MPR Teltech Research Chair in RF Engineering, Department of Electrical & Computer Engineering,
University of Victoria, P.O. Box 3055, Victoria, B.C., Canada, V8W 3P6.
* Schumberger GeoQuest, Abingdon, Oxfordshire, UK.

ABSTRACT

A time domain model based on the Transmission Line Matrix (TLM) method for the RF drying of wood in a vacuum kiln is presented. The model is capable of addressing critical issues for the material processing industry such as drying time, penetration of the electromagnetic field into the material and evaluation of critical location where arcing may occur. The control and optimization of all of these variables leads to a highly efficient drying process yielding dry wood faster and with a higher quality compared to traditional convection drying. In addition the modeling of mass transfer and heat diffusion processes allows us to monitor temperature and moisture pressure in the wood sample so that critical values are not exceeded.

INTRODUCTION

Industrial applications of high frequency electromagnetic field are growing in number and scope. In particular a whole new field of material processing is now emerging with application of high power electromagnetic fields to, sintering, cooking, drying of biopolymers, and waste treatment [1].

The large majority of these applications are based on the use of RF or microwaves to heat the material under process with a defined heating pattern. In order to accurately predict the heating pattern a coupled electromagnetic/heat diffusion model must be developed so that not only the electromagnetic field in the material can be determined, but also its evolution as the material properties change under the effect of the energy dissipated in that volume.

Research in this direction has been developed in [2]-[4]. In this contribution we focus on the application of electromagnetic fields to drying wood products. The advantage of RF drying of wood and other biopolymers are multiple;

- the application of RF energy can be accompanied by creating vacuum conditions in the kiln (RF/V kilns). In this way moisture is evaporated at a lower temperature and with a lower amount of deposited energy,
- the frequency of operation (in this case 6.78 MHz) results in a large penetration depth of the wave in the material, thus heating much deeper than what conventional convection heating would allow,
- the wood undergoes a lower degree of stress, thus resulting in a drying process with a higher yield,
- the drying process is much faster than conventional drying (up to an order of magnitude) and leads to a more uniform moisture profile.

THEORY

The structure we have considered is shown in Figure 1. It represents the experimental RF/V kiln available at the Department of Wood Sciences at the University of British Columbia (UBC).

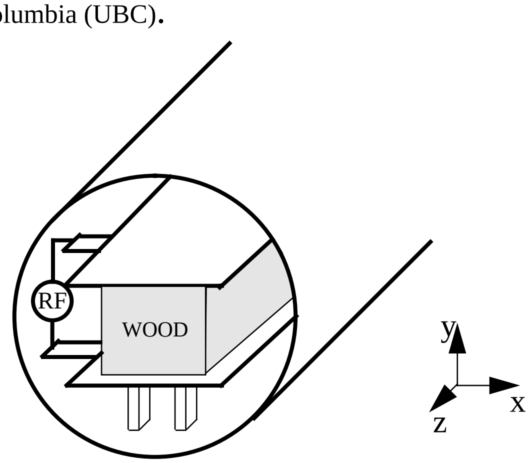

Figure 1. UBC RF/V kiln.

The kiln is a steel circular cylinder (that has been approximated as a square cylinder for the initial testing of the

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method) that can accommodate wood samples of maximum size: 0.35 by 0.35 by 2.7 m.

The sample rests on the lower metallic applicator, while the upper applicator is lowered until it touches the wood. The RF source is capable of delivering up to 10 KW at the frequency of 6.78 MHz. The design of this basic kiln resembles that of a parallel plate capacitor, and one would assume the electromagnetic field between the plates to be constant. However this is not the case since the outside chamber is grounded and the wood sample significantly perturbs the EM field. The kiln geometry thus results in a highly complex field structure for which a fully numerical method must be used.

To develop the numerical model of the RF/Vacum drying of wood we must address the following phenomena:

- Electromagnetic field distribution in the wood and the surrounding kiln,
- Energy deposition which increases the mobility of moisture in the lumber,
- Heat transfer and
- Mass transfer which, in turn, changes the dielectric properties of the wood.

All of these phenomena must be coupled in a self-consistent numerical model. Because of the time varying parameters of the wood during the drying cycle, we have chosen to use a time domain method.

In particular, while the electromagnetic problem is solved in a time stepping procedure by means of the TLM method, the diffusion of heat and moisture in the wood is solved by Fine Differences Time Domain (FDTD).

Due to the vastly different time scales for the E/M propagation and for the diffusion processes an alternating scheme has been used. First the E/M field in every point in the kiln is computed with TLM. The cuboid hybrid formulation is used in this case.

The FDTD mesh is then arranged as to overlap with the TLM mesh. In this way no averaging is necessary to obtain the dissipated power in each thermal cell.

Then, using the RF power dissipated in each region as a source for the diffusion equations, the heat and moisture transfer equations are solved until a significant change in material parameters (ε’ and tan(δ)) is detected.

The new parameters are returned to the E/M code for TLM to generate the new field configuration. The whole process is iterated until the wood is completely dry.

The TLM method is ideal for tracking the time varying material properties of the wood, and its stability under these changing conditions is very valuable. On the other hand, the FDTD scheme allows a direct implementation of the diffusion process even for coupled heat/moisture equations (equations 1 and 2). Figure 2 summarizes the algorithm used.

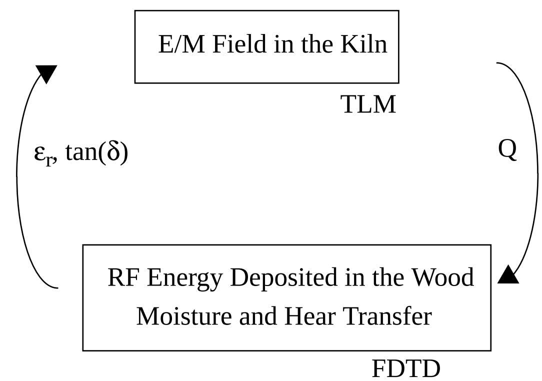

Figure 2. Modeling algorithm for the coupled electromagnetic/ heat diffusion/ moisture diffusion phenomena.

Because the placement of the wood in the kiln usually aligns the wood fibers with the kiln axis, only diagonal tensors for the permittivity and permeability are necessary. Time varying ε’ and tan(δ) are considered and can be specified via interpolated functions (related to the temperature and moisture content in that region of wood) or via look-up tables. In this way different wood species and other biopolymers can be modeled.

The thermal code model is a discrete formulation of the heat and moisture diffusion. The equation under considerations are:

$$\frac{\partial M}{\partial t} = \nabla(D_M \nabla M) + \nabla(D_T \nabla T) \tag{1}$$

$$\rho c_p \frac{\partial T}{\partial t} = \nabla(\lambda_T \nabla T) + \nabla(\lambda_M \nabla M) + Q \tag{2}$$

where ρ is the wood density, c_p is the wood specific heat, T is the temperature in the wood, M is the moisture content and Q is the energy applied via radio frequency. The coefficients D_M, D_T, λ_M, λ_T are the diffusivity coefficients for the moisture and the heat. The presence of these coefficients means that either heat as moisture diffusion can occur in the presence of a gradient of both heat and moisture. According to Avramidis et al [5] the equations can be simplified as:

$$\frac{\partial M}{\partial t} = \nabla(D_M \nabla M) \tag{3}$$

$$\rho c \frac{\partial T}{\partial t} = \nabla(\lambda_T \nabla T) + Q \qquad (4)$$

where D_M and λ_T depend on the temperature and on the moisture content; $D_M = D_M(M, T)$ and $\lambda_T = \lambda_T(M, T)$.

The above differential equations have been discretized with the Finite Differences in the Time Domain (FDTD) based on the FTCS (Forward Time Central Space) scheme [6].

RESULTS

The model has been applied to the drying of western hemlock (a common wood species in British Columbia, Canada). The dielectric properties of this wood over a wide variety of moisture contents, temperatures and frequencies have been obtained from available data [5].

The diffusion coefficients have been derived from available literature [7] and from empirical and experimental data [5].

Figure 3 and 4 show the transverse diffusion coefficients for the thermal and the moisture diffusion processes. Note how the values change with moisture and temperature. The change in behavior around the value of moisture content equal to 30% (so called fiber saturation point, FSP) corresponds to a change in the physics governing the moisture diffusion process.

The longitudinal values are related to the transverse values by factors that can be considered approximated constant:

$$D_z = 2.5 D_T \qquad \lambda_z = 2\lambda_T \qquad (5)$$

Note in Figure 4 that the diffusivity for the moisture equation can change over up to two orders of magnitude. A very robust algorithm is therefore required to handle such widely varying coefficients.

The specific heat as well as the wood density also changes with the moisture content and their effect was included in the model.

The simulation of the drying cycle is carried out in three steps. In step 1 the kiln is turned on and the electromagnetic field is established in the structure without activating the thermal code. In step 2 the thermal code and the E/M code are stepped until the average moisture content in the wood reduces to 10% (dry wood). In step 3 the thermal code is deactivated and the E/M code run until the final steady state field is reached.

Figure 5 shows the evolution of the moisture content in the center of the wood sample. Note that in the vicinity of the FSP a change in behavior occurs. This is due to the physical change in the diffusion process. Figure 6 shows the temperature evolution in the same point in the sample.

The procedure allows monitoring the E/M field in the kiln, the moisture content and temperature in each point in the sample, as well as other quantities available in the method. This allows the user to visualize and control these quantities in order not to exceed critical values in terms of electromagnetic field (not to create arcing), temperature (not to burn the wood) and water pressure (not to rupture the wood fibers).

Measurements to validate the simulated results in the experimental kiln at the University of British Columbia are in progress. One of the critical factors in this validation is the determination of the diffusion coefficients, which are known only through empirical and experimental data. Reliable measurements coupled with an accurate simulation can therefore also be used to reverse-engineer these critical coefficients and to shade light on the physics of the RF/V drying process.

CONCLUSIONS

A time domain model for the RF drying of wood in a vacuum kiln has been developed. The method is based on a time stepping approach to solve the electromagnetic field in the wood and the surrounding kiln (solved with the TLM method) and the diffusion equations for the moisture and the heat in the wood (solved with the FDTD method). Experimental investigations in a experimental kiln are under progress in order to calibrate the model and gain more confidence in the simulated results. Nevertheless, the results obtained are in agreement with typical drying curves and with the physics of the drying process.

In addition by changing diffusion coefficients the method can be easily extended to RF processing of other biopolymers.

ACKNOWLEDGEMENTS

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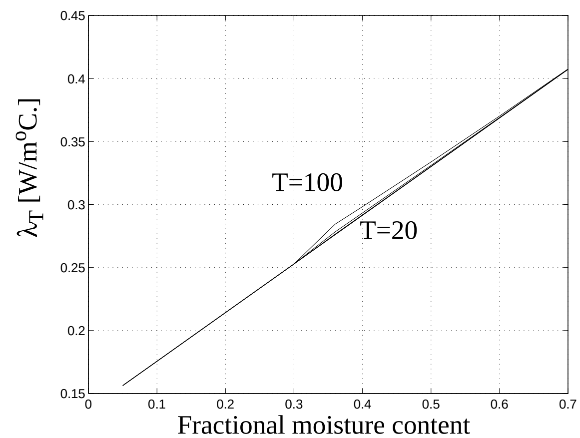

Figure 3. Values of transverse diffusion coefficient for the heat diffusion process as a function of moisture and temperature. Temperatures in ^{o}C.

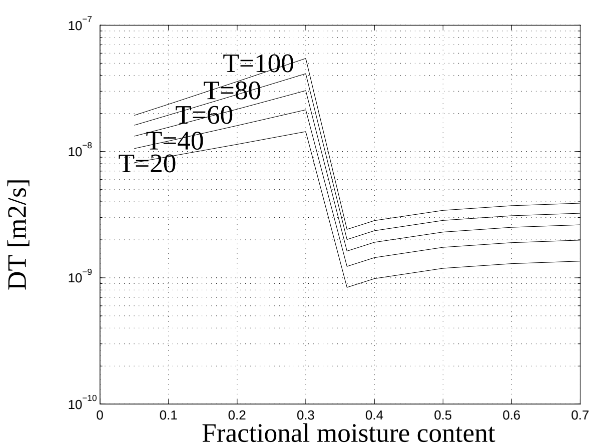

Figure 4. Values of transverse diffusion coefficient for the moisture diffusion process as a function of moisture and temperature. Temperatures in ^{o}C.

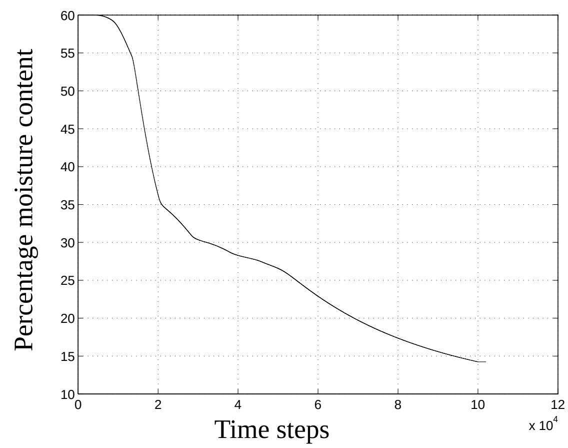

Figure 5. Evolution of the percentage moisture content in the center of the wood sample when RF energy is applied.

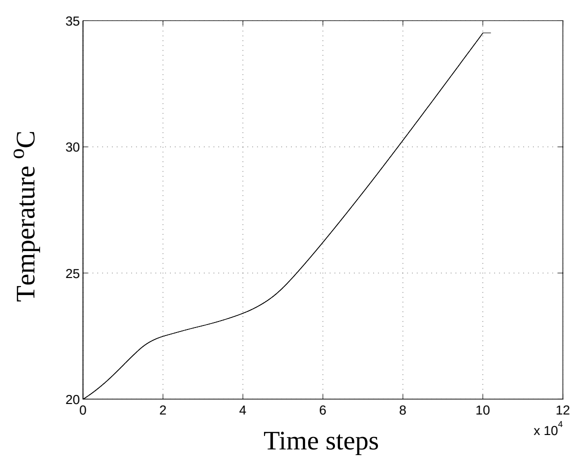

Figure 6. Evolution of the temperature in the center of the wood sample when RF energy is applied.

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