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Sensitivity Study of a Numerical Model of Heat and Mass Transfer Involved During the MDF Hot Pressing Process

Zanin KAVAZOVIĆ
GIREF, Département de mathématiques et de statistique, Pav. Vachon
1045, av. de la Médecine, Université Laval
Québec (QC) G1V 0A6, Canada

Alain CLOUTIER
CRB, Département des sciences du bois et de la forêt
Pav. Gene-H.-Kruger, Université Laval
Québec (QC) G1V 0A6, Canada

André FORTIN, Jean DETEIX
GIREF, Département de mathématiques et de statistique, Pav. Vachon
1045, av. de la Médecine, Université Laval
Québec (QC) G1V 0A6, Canada

Abstract

The hot pressing of MDF is a complex process involving several heat and mass transfer properties of the fiber mat. A sensitivity study of the heat and mass transfer model to the mat physical properties is performed in the current study. The mathematical model is based on the conservation of heat, air, and water vapor. The three state variables of the problem are temperature, air pressure, and vapor pressure. They depend on many parameters describing the material properties of the mat. Most of these parameters are known with a limited degree of accuracy (measurements made on wood or on manufactured panels). Also, mats made from fibers of different morphology will have different properties. Therefore, there is a need to account for variability and uncertainty in the material properties and to estimate their impact on the accuracy of the predicted results. In this sensitivity study, we perform "what if" scenarios with regard to material properties in order to predict the system's response and the solution's behavior as a consequence of the variability in the mat physical properties. Our study suggests that the heat conductivity has a very significant influence on the heat and mass transfer phenomena within the mat. Also, the decrease in gas permeability is an influential factor affecting the dynamics during the hot pressing. The convective heat transfer coefficient on the external boundary does not seem to have a significant influence on the results. This somewhat surprising finding requires further investigation. On the other hand, the convective mass transfer coefficient on the external boundary has an enormous influence on the state variables. Hence, accurate measurements of this parameter are needed in order to improve the quality and the reliability of the numerical results.

Keywords: Sensitivity study, hot pressing, heat and mass transfer, finite element method.

Introduction

The hot pressing of MDF is a complex process that has captured attention of many researchers in the last years. The literature proposes different heat and mass transfer models for the hot pressing process of wood-based composite panels such as MDF, OSB and particleboard (Carvalho and Costa 1998, Dai and Yu 2004, Zombori et al. 2003, Thömen and Humphrey 2006, Nigro and Storti 2006). Ultimately, all of the heat and mass transfer models are based on the conservation of heat, air mass and water vapor mass (Zombori et al. 2003, Dai and Yu 2004, Thömen and Humphrey 2006). To these conservation laws one can add cure kinetics equation of the adhesive system which allows one to predict the evolution and the degree of the resin cure (Zombori et al. 2003, Loxton et al. 2003).

The predicted solutions obtained by solving the system will depend on several heat and mass transfer parameters describing the material properties of the fiber mat. These parameters are only known with a limited degree of accuracy, especially under conditions prevailing during the hot pressing process. Moreover, most of the material properties come from measurements made on wood or on manufactured panels (von Haas et al. 1998). Furthermore, mats made from fibers of different morphology will surely have different properties. We understand that such particularities have an impact on the accuracy of the predicted results. Clearly, there is a need to account for variability and uncertainty in the material properties and to estimate their impact on the accuracy of the predicted results. In order to improve the reliability of a mathematical model, we shall look at the impact of variations in material properties on the predicted numerical solutions. Therefore, the model's sensitivity to the parameters characterizing the heat and mass transfer in the fiber mat should be examined (Zombori et al. 2004). Our objective is to conduct a sensitivity study in order to better understand the influence that variations in physical parameters have on the numerical solution of the heat and mass transfer model.

Methodology

In the present work, we focus on the influence of heat conductivity, gas permeability and convective heat and mass transfer coefficients associated to the boundary conditions on the solution's behavior. The contribution of resin cure to heat and mass transfer is not taken into account. We assume that the initial mat moisture content is uniform throughout the thickness. A predefined oven-dry density profile is used during the simulation runs.

Model of Heat and Mass Transfer in the Fiber Mat

We retained the mathematical model proposed by Thömen and Humphrey (2006). The model is based on the conservation of heat, air, and water vapor. The original version of this model is restated as follows in terms of the three state variables: partial air pressure

(P_a), partial water vapor pressure (P_v) and temperature (T)

Conservation of mass of the AIR

$$\frac{\partial(\rho_a \Phi)}{\partial t} - \nabla \bullet \left(\left[\frac{\rho_a}{\mu} K_p + \frac{M_a}{RT} D_{eff} \right] \bullet \nabla P_a \right) - \nabla \bullet \left(\frac{\rho_a}{\mu} K_p \bullet \nabla P_v \right) = 0 \qquad (1)$$

Conservation of mass of the WATER VAPOR

$$\frac{\partial(\rho_v \Phi)}{\partial t} - \nabla \bullet \left(\frac{\rho_v}{\mu} K_p \bullet \nabla P_a \right) - \nabla \bullet \left(\left[\frac{\rho_v}{\mu} K_p + \frac{M_v}{RT} D_{eff} \right] \bullet \nabla P_v \right) = -\rho_{OD} \frac{\partial M}{\partial t} \qquad (2)$$

Conservation of ENERGY

$$\rho_{Mat} C_{Mat} \frac{\partial T}{\partial t} - H_{fg} \rho_{OD} \frac{\partial M}{\partial t} - \nabla \bullet \left(K_T \bullet \nabla T \right) = 0 \qquad (3)$$

where ρ_{OD} is the oven-dry density of the mat [kg/m^3], $\Phi = 1 - \frac{\rho_{OD}}{1530}$ is the porosity of the mat [dimensionless], $\rho_{Mat} = \rho_{OD}$*(1+M) is the wet density of the mat [kg/m^3] and μ is the dynamic viscosity of the air-vapor mixture [Pa s].

Using the Malmquist sorption model (Malmquist 1958, Vidal and Cloutier 2005), we can also predict and monitor the mat moisture content. As proposed by Vidal (2006), the chain rule is applied and the term $\frac{\partial M}{\partial t}$ is developed as $\frac{\partial M}{\partial t} = \frac{\partial M}{\partial P_v}\frac{\partial P_v}{\partial t} + \frac{\partial M}{\partial T}\frac{\partial T}{\partial t}$. This developed expression is then substituted into the Equations (2) and (3).

For each of the three conservation equations (Eqs. (1), (2) and (3)), a finite element method discretization is performed in space while the time derivatives are calculated using the Euler implicit scheme. At each time step, Equations (1), (2) and (3) are simultaneously solved by a fixed point method allowing to predict the evolution of the state variables in space and over time.

Boundary Conditions

To properly solve the Equations (1), (2) and (3), appropriate boundary conditions are needed. On the surface in contact with the hot platen, the temperature evolution was imposed from the data obtained during in-situ laboratory experiments. The hot platen is assumed impervious to gas and zero air and vapor fluxes are considered. On the edge in contact with the ambient air, the following Robin (exchange) boundary conditions are imposed to the three state variables: temperature, air pressure and vapor pressure:

$$\text{Heat flux : } q_T = - h_T * (T - T_{amb}) \quad (4)$$

$$\text{Air flux : } q_{Pa} = - h_p * \frac{\rho_a}{\mu} * (P - P_{amb}) \quad (5)$$

$$\text{Vapor flux : } q_{Pv} = - h_p * \frac{\rho_v}{\mu} * (P - P_{amb}) \quad (6)$$

where h_T is the convective heat transfer coefficient [J/(s m^2 K)] and h_p is the convective mass transfer coefficient [m] (both of them are presented later with more details).

Sensitivity Study

The state variables (P_a , P_v , T) depend on many parameters describing the material properties of the mat. A sensitivity study of the heat and mass transfer model to the mat physical properties is therefore performed. In this sensitivity study, we perform "what if" scenarios with regard to material properties in order to predict the system's response and solution's behavior as a consequence of this variability. An intuitive and simple approach consists of keeping all the parameters constant with an exception of one parameter which is allowed to vary.

The results obtained using reference values of the material properties proposed in the literature will be compared to results obtained with disturbed values of the material properties. To some extent, the perturbation factors can be seen as uncertainty or measurement errors of the material property of interest. Hence, a disturbed value of a material property of interest is obtained by multiplying the reference expression by a given factor (Eg: 1.2 for a perturbation (increase) of 20%, 0.5 for a perturbation (decrease) of 50%). The results are presented for the following multiplying factors: 0.5; 0.8; 1.2; 2.

Results Comparison

The solution obtained with the disturbed value of the parameter will be compared to that obtained using the reference value of the parameter of interest. The resulting discrepancy between those solutions can be quantified in different ways. We will express it as a percentage of the relative difference. For instance, T_{ref} denotes the temperature field calculated using the reference expression and T_{per} is the temperature calculated using a disturbed value of a parameter of interest, then

$$100 * \frac{(T_{per} - T_{ref})}{T_{ref}} \quad (7)$$

is the percentage of relative difference depicting the impact of variation of a given parameter on the temperature field. At each time step, we calculate and plot the maximum value of the expression above. This generic approach is used for other variables of interest as well.

Results and Discussion

Heat Conductivity K_T [J/(s m K)]

We used the expression suggested by Thömen and Humphrey (2006) as a reference value for the heat conductivity of the fiber mat: $K_{Txy} = 1.5*K_{Tz}$ where $K_{Tz} = K_{T030} + \Delta K_T$ with
$K_{T030} = 4.38*10^{-2} + 4.63*10^{-5}*\rho_{OD} + 4.86*10^{-8}*\rho^2_{OD}$ the thermal conductivity measured at 0% moisture content and $30°C$ and the correction term accounting for moisture content and temperature effects on thermal conductivity $\Delta K_T = 0.49*M + (1.1e\text{-}4 + 4.3e\text{-}3*M)*(T-303.15)$.
K_{Tz} is a thermal conductivity in thickness direction and K_{Txy} is a thermal conductivity in horizontal plane (xy plane). Figure 1 presents the impact of variations in K_T as a percentage of the relative difference for both temperature and total pressure.

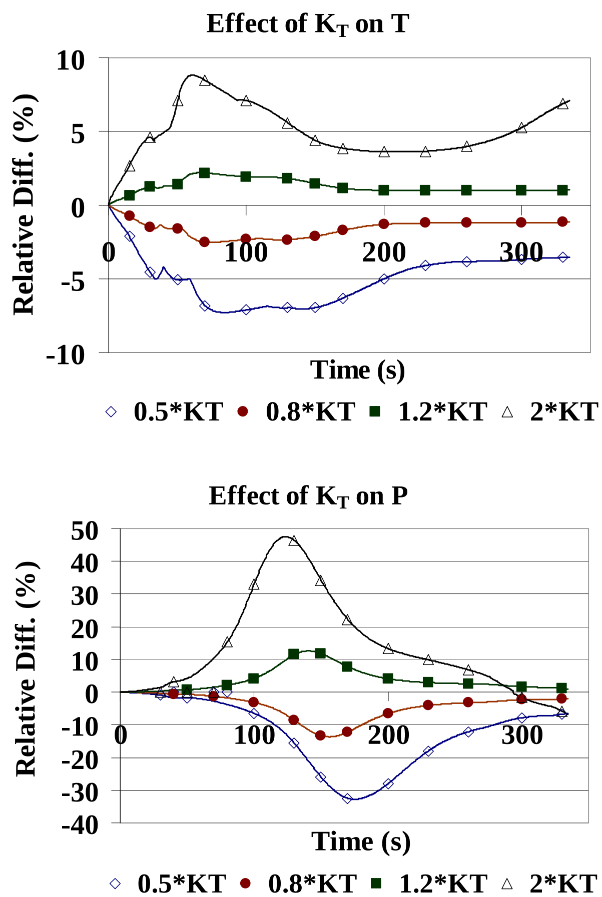


Figure 1 : *Impact of heat conductivity on temperature and total pressure.*

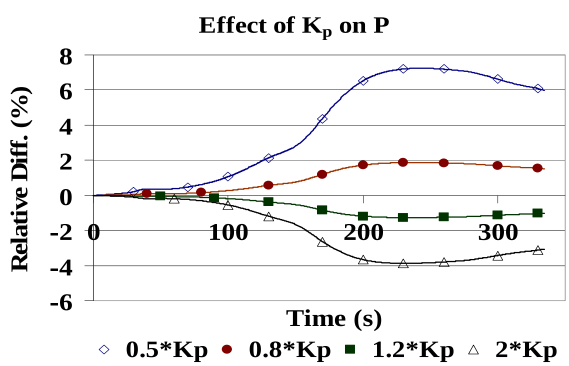
The heat conductivity has a very significant influence on the mass transfer in the mat during the hot pressing process. Indeed, variations in K_T have an effect on gas pressure within the mat almost 5 times higher than on temperature.

Specific Gas Permeability of the Mat K_p [m^3/m]

Analytical expressions for the specific gas permeability of MDF mats based on the curve fitting of experimental data can be found in Garcia and Cloutier (2005) and also in von Haas et al. (1998). The expression proposed by Garcia and Cloutier (2005) is valid for MDF mats having a density between 400 kg/m^3 and 1150 kg/m^3, whereas in von Hass et al. (1998) the permeability of fiber, particle and strand mats with densities varying from 200 kg/m^3 to 1200 kg/m^3 was determined. In our study, the reference expression and the input data for the specific gas permeability of the MDF mats will be based on expressions proposed by von Haas et al. (1998):

$Kp = \exp(1/A)$ where $A = a + b*\rho_{Mat} + \dfrac{c}{\ln(\rho_{Mat})}$ and coefficients to determine in-plane permeability (K_{pxy}) for MDF fiber mats are $a = -0.041$, $b = 9.51*10^{-6}$, $c = -0.015$ and those for cross-sectional (K_{pz}) permeability for MDF fiber mats are
$a = -0.037$, $b = 1.1*10^{-5}$, $c = -0.037$.

Figure 2 shows that gas permeability is a significant factor affecting mostly mass transfer in the mat.



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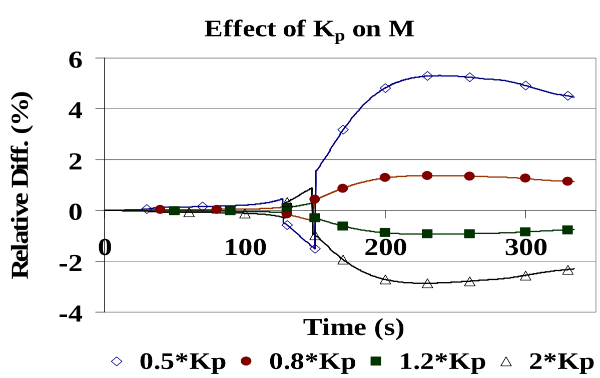

Figure 2 : *Influence of gas permeability on total pressure and moisture content.*

It can also be noticed that the decrease in gas permeability has a more pronounced effect on the solution than the proportional increase of gas permeability.

Heat Transfer Coefficient on the External Boundary h_T [J/(s m^2 K)]

The sensitivity of the system's solution to variations in the heat transfer coefficient associated to the external boundary will be examined. The reference value for this parameter (h_T = 0.35) is taken from Vidal (2006) and Zombori (2001).

As depicted in Figure 3, the external boundary heat transfer coefficient does not seem to have a significant influence on the heat and mass transfer phenomena within the mat. This result is somewhat surprising and further explorations might be required in order to improve our understanding of these results.

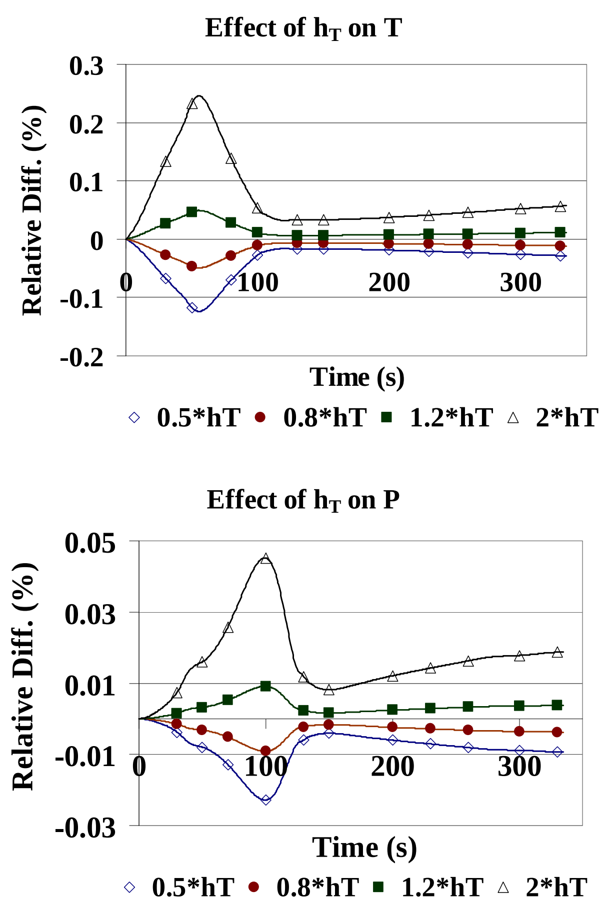

Figure 3 : *Influence of external heat transfer coefficient on temperature and total pressure.*

Mass Transfer Coefficient on the External Boundary h_p [m]

The mass transfer coefficient represents the mat boundary gas transport properties and depicts the resistance to gas flow out of the mat. We examine the importance of this external bulk flow coefficient associated to the boundary condition imposed on the edge in contact with the ambient air. We take $h_p = 10^{-11}$ as a reference value of this coefficient.

Figure 4 summarizes the impact that the external mass transfer coefficient has on the system. One observes that this coefficient has a very significant influence on heat and mass transfer within the mat during the hot pressing process. This effect can not be ignored. Indeed, the reactions of the system to variations of h_p are comparable in importance to those created by K_T. Hence, we believe that accurate estimates/measurements of this parameter are needed in order to improve the quality and reliability of predictions produced by a physical-mathematical model.

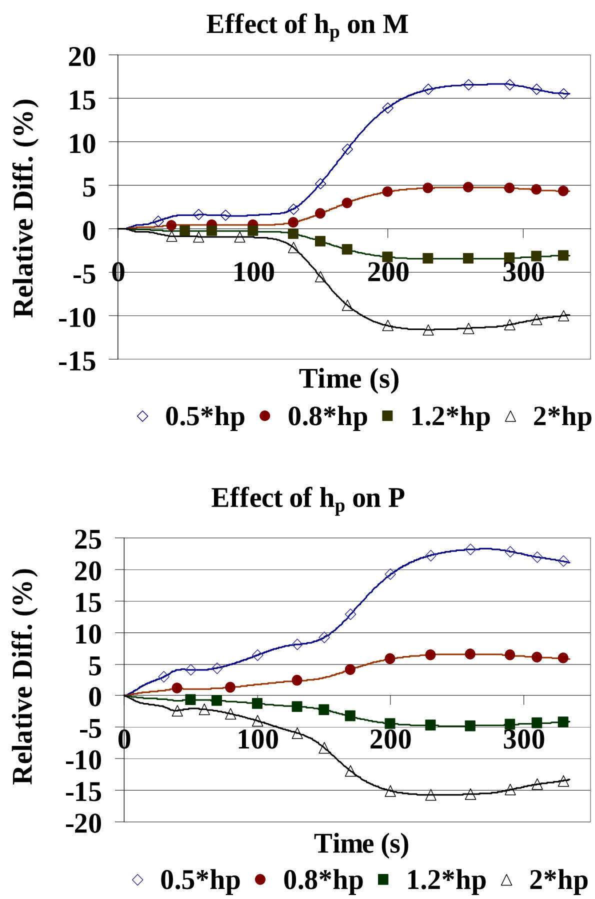

Figure 4: *Influence of external convective mass transfer coefficient on moisture content and total pressure.*

Conclusions and Future Work

The results obtained from this sensitivity study allow to improve our understanding of the influence of different material properties in the mathematical model. At each time step, the overall maximal value of the percentage of relative difference between the solution obtained with a reference value of a parameter of interest and the solution attained using a disturbed value of the same parameter is suggested as a tool to quantify the influence of the parameter of interest on the system's behavior. These results enable the optimization of the human and material resources for the characterization of the most significant parameters in order to improve the reliability of the numerical results.

Our study suggests that, among the tested material properties, those having the most pronounced effect on the heat and mass transfer within the mat during the hot pressing process are the thermal conductivity of the mat and the convective mass transfer coefficient associated to the edge in contact with the ambient air. Given that the latest coefficient plays a very important role in the quality of the results produced by the model, significant efforts should be made in order to get accurate measurements of this coefficient.

It would be interesting to study the impact of different sorption models on the outcome of numerical simulations. Additionally, an alternative tool, the L2-norm, could be used to quantify the influence of a parameter of interest on the system's behavior. These aspects will be covered in our upcoming publications.

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