

Fundamentals of flakeboard manufacture: wood-moisture relationships *

F. A. Kamke and M. P. Wolcott, Blacksburg, VA, USA

Summary. A procedure is presented to estimate the relative vapor pressure, equilibrium moisture content, average flake temperature, and average flake moisture content in a flakeboard mat during hot-pressing. This method is based on measurements of temperature and total gas pressure in the mat during hot-pressing. A heat and mass transfer model was adapted from the literature to predict the temperature and moisture content inside an individual flake. Significant moisture gradients are predicted to develop within flakes. Convective heat transfer appears to control the change of moisture content within a flake. Thermodynamic equilibrium between the gas phase and the wood component is not achieved during hot-pressing.

Introduction

The wood component in a flakeboard mat during hot-pressing is subjected to rapidly changing gas pressure, temperature, and humidity (Kamke, Casey 1988 a, b). Temperature and moisture gradients are developed within the mat, which influence mechanisms involved in the panel formation. Extremes in temperature and moisture content affect the adhesive cure and penetration (Brady, Kamke 1988; Chow, Mukai 1972), which in turn affect the bond quality. The interaction of temperature, moisture content, and compaction pressure is responsible for the formation of a vertical density gradient in the panel (Strickler 1959; Wolcott et al. 1989). The local density will influence the physical properties of the panel as a result of the bonding area between adjacent wood elements (Back 1988), flake damage (Geimer et al. 1985), and the amount of cell wall substance per unit volume of panel.

Mathematical models have been developed to predict internal mat temperature and moisture content in particleboard during hot-pressing (Humphrey 1979; Kayihan, Johnson 1983; Harless et al. 1987). These models treat the flakeboard mat as a continuum with a characteristic void volume. Local thermodynamic equilibrium is assumed, therefore, any resistance to heat and mass transfer between the gas phase and the adjacent wood component is neglected. This may produce predicted mat temperatures and moisture contents that differ from those inside a wood flake.

* This work was funded by the USDA Competitive Grant Program for Forest and Rangeland Renewable Resources, Project No. 85-FSTY-9-0106 and 87-FSTY-9-0253

Methods have not yet been developed to experimentally measure the moisture content of the wood component in mats during hot-pressing. However, the in situ temperature and total gas pressure can be measured (Humphrey 1979; Kamke, Casey 1988 a, b). These parameters can then be used to describe the composition of the gas phase surrounding the wood component. An exchange of heat and mass will occur across the boundary of the wood component as the system moves toward thermodynamic equilibrium. Some resistance to temperature and moisture movement must exist at the surface of the wood elements. Previous models account for this resistance by incorporating this effect into experimentally derived heat and mass transfer coefficients for the mat continuum.

Convective heat and mass transfer coefficients have been calculated for fixed and fluidized beds of granular materials (Frantz 1961; Toei et al. 1967; Treybal 1980). These coefficients are used to describe the transfer of heat or mass from the gas phase to the solid phase in the granular bed. If the composition of the gas phase and the transport resistances surrounding a wood flake can be measured or predicted, then the necessary boundary conditions would be available as inputs for a heat and mass transfer model of an individual flake. A model for predicting heat and mass transfer in wood is available (Stanish et al. 1985). Therefore, it is possible to use generalized equations and models that were derived independently of wood-flake mats to predict the change of temperature and moisture content of individual wood flakes during hot-pressing. This approach, however, does require knowledge of the gas phase composition within the flakeboard mat.

The objectives of this work were:

1. To develop a method for estimating the gas phase composition in a flakeboard mat during hot-pressing.
2. To use a previously developed heat and mass transfer model for wood to estimate the flake temperature and moisture content during hot-pressing.
3. To assess the amount of resistance to heat and mass transfer at a surface of a flake during the hot-pressing operation.

Methods

High temperature EMC

Sorption models have long been used to predict the equilibrium moisture content (EMC) of wood as a function of relative humidity and temperature (less than 100°C) (Simpson 1971, 1973). Simpson (1973) evaluated several types of sorption equations for their ability to describe the EMC data listed in the Wood Handbook (U.S. Forest Products Laboratory 1987). When a non-linear regression technique was used to perform the curve-fitting, Simpson judged that the two-hydrate form of the Hailwood-Horobin equation provided the best fit. This equation has been used to describe the EMC in heat and mass transfer models for wood. The equation and coefficients determined by Simpson (1973) are:

$$\text{EMC} = \frac{1800}{W} \left[\frac{KH}{1-KH} + \frac{K_1 KH + 2 K_1 K_2 K^2 H^2}{1 + K_1 KH + K_1 K_2 K^2 H^2} \right] \quad (1)$$

where

$$\begin{aligned}
 W &= 349 + 1.29T + 1.35 \times 10^{-2} T^2; \\
 K &= 8.05 \times 10^{-1} + 7.36 \times 10^{-4} T - 2.73 \times 10^{-6} T^2; \\
 K_1 &= 6.18 + 5.07 \times 10^{-3} T - 3.00 \times 10^{-4} T^2; \\
 K_2 &= 2.39 + 2.56 \times 10^{-2} T - 3.03 \times 10^{-4} T^2; \\
 H &= \text{relative vapor pressure}; \\
 T &= \text{temperature } (^\circ\text{C}).
 \end{aligned}$$

Whereas average sorption relationships are well documented for wood at low temperatures, data at elevated temperatures (higher than 100 °C) are limited. Simpson and Rosen (1981) reviewed the literature for both experimental and extrapolated data on wood moisture contents at one atmosphere pressure and elevated temperatures. They concluded that the data for elevated temperatures could be adequately described using the one hydrate form of the Hailwood-Horobin equation, with the parameters presented for the low temperature sorption data by Simpson (1971). However, the two-hydrate form of the Hailwood-Horobin theory was not evaluated. In addition, Resch et al. (1988) published data on sorption characteristics of yellow poplar (*Liriodendron tulipifera*) at high temperatures and pressures greater than one atmosphere. The elevated temperature data presented by Simpson and Rosen (1981) for one atmosphere of pressure, and the data by Resch et al. (1988) at pressures greater than one atmosphere, were evaluated in this study using both the one and two-hydrate forms of the Hailwood-Horobin equation. The coefficients used in the equations are the same as presented by Simpson (1971, 1973).

The experimental EMC values were compared to the results from the empirical equations using the root mean square error (Benjamin, Cornell 1970), which is a measure of the average deviation that can be expected over the range of experimental values. Table 1 displays the mean square error and the maximum deviation for both equations and data sets. Less error exists between the predicted and measured EMC for the data collected at one atmosphere of pressure than at the elevated pressures. The predictions are poorest for the pressurized conditions at 140 °C. The data at this temperature is suspect because the desorption isotherm lacks the sigmoidal form exhibited at 120 °C and 160 °C (Resch et al. 1988).

An analysis of covariance was used to determine if a statistical difference existed between the individual regression lines of the experimental EMC values versus the

Table 1. Analysis of covariance for the one and two hydrate forms of the Hailwood-Horobin sorption model fitted to EMC data for wood above 100 °C. Data is from Simpson and Rosen (1981) and Resch et al. (1988)

Model	Total pressure atm	Coefficient of variation	Root mean square error % MC	Maximum deviation % MC
1-Hydrate	1	12.8	0.90	2.1
	>1	29.5	1.23	4.4
2-Hydrate	1	11.6	0.86	3.7
	>1	27.6	1.19	4.7

predicted EMC (Snedecor, Cochran 1967). This analysis showed that no significant difference can be discerned among the regression lines for these four comparisons at the 0.05 alpha level.

It has been shown that the predicted EMC can vary substantially from the experimental EMC under certain conditions. However, considering the limited experimental data, we have chosen to use the two-hydrate form of the Hailwood-Horobin equation presented by Simpson (1973).

Estimating the gas phase composition

When the flake mat is initially compressed some air and water vapor is trapped within the void network. Because the voids are small, the wood component controls the water vapor content. Subsequent heating of the outer surfaces of the mat rapidly generates water vapor, thus increasing the total gas pressure at the surface. The positive pressure differential between the surface and the core results in the hydrodynamic flow of heat-laden water vapor to the core of the mat. In the core, the incoming water vapor is mixed with the existing environment. Condensation in the core is possible. The addition of water vapor from the surface causes an increase of total pressure in the core. A positive pressure differential is established from the interior of the mat laterally to the edges. Thus, a mixture of water vapor and air will flow through the edges of the mat. The air in the gas phase will never be replenished during hot-pressing. Therefore, the mole fraction of the air in the voids will continually decline.

A series of plots of temperature and total gas pressure in the core of flake mats during hot-pressing were presented by Kamke and Casey (1988b). The total gas pressure rises until the rate of dissipation through the edges of the mat exceeds the rate of water vapor generation. This occurs when the bound water supply is nearly depleted or the lateral permeability of the mat increases as a result of venting.

The environmental variables measured inside a mat during hot-pressing are temperature and total gas pressure. However, the bound water content in wood responds to changes in temperature and water vapor pressure. To describe the moisture content change of the wood component, the relative water vapor pressure in the mat can be calculated based on local temperature and total gas pressure data. At the beginning of the press cycle the initial relative vapor pressure inside the mat is determined from the initial mat moisture content and temperature using an inverted form of Eq. (1). The initial water vapor pressure is calculated as:

$$p_w = H p_{\text{sat}} \quad (2)$$

where

H = relative vapor pressure

p_{sat} = saturated vapor pressure, atm.

The p_{sat} is calculated using the empirical equation derived by Stanish et al. (1985):

$$p_{\text{sat}} = \frac{RT}{18} e^Q \quad (3)$$

where

$$Q = -46.49 + 0.26179 T - 5.0104 \times 10^{-4} T^2 + 3.4712 \times 10^{-7} T^3$$

R = gas constant = 0.08206 atm m³/mol K

T = temperature (K).

The water vapor content is defined as:

$$C = \frac{P_w}{P} \quad (4)$$

where

C = water vapor content, moles of water vapor/total moles of gas

P = total gas pressure, atm.

The water vapor content at any other time during the press cycle is estimated based on the following assumptions:

1. At any location in the mat the change in total gas pressure results from the internal generation of water vapor, hydrodynamic flow from other regions in the mat, and a temperature effect as defined by the ideal gas law.

2. Gas continuously leaks through the edges of the mat. The rate of leakage is proportional to the pressure differential. The leakage coefficient is constant over time and location in the mat.

3. Air is not replenished in the mat. The water vapor content will not decrease during hot-pressing.

4. Only water vapor and air are present in the gas phase.

From assumption 4, the total gas pressure is comprised of the partial pressures of the water and air:

$$P = p_w + p_a = p_w + (1 - C) P. \quad (5)$$

Substituting the ideal gas law for the partial pressure terms yields:

$$P = (c_w + c_a) RT \quad (6)$$

where

c_w = molar concentration of water vapor, mol/m³

c_a = molar concentration of air, mol/m³.

Differentiating Eq. (6) with respect to time gives:

$$\frac{dP}{dt} = RT \left[\frac{dc_w}{dt} + \frac{dc_a}{dt} \right] + R(c_w + c_a) \frac{dT}{dt}. \quad (7)$$

The time derivative of the molar concentration of water vapor is dependent on internal generation of water vapor, flow inside the mat, and leakage out of the mat. This analysis is concerned with the conditions at a point in the mat. Therefore, the mechanisms that are responsible for the change in molar concentration of water vapor are not separated, and this term is treated as a dependent variable.

The molar concentration of the air is dependent on flow inside the mat and leakage out of the mat. The significance of the leakage is that it results in a continuous

decrease in the partial pressure of air. Assumption 3 states that air is not replenished, therefore, the water vapor content C , will increase in addition to the amount resulting from internal generation. The transport mechanisms affecting air flow cannot be separated using this analysis. In order to account for the change in water vapor content as a result of leakage, an apparent mat permeability factor was defined to relate the relative change of the molar concentration of air to the total pressure differential between the interior of the mat and the ambient environment.

$$\frac{dc_a}{dt} = -(1-C) K (P - P_{amb}) \quad (8)$$

where

K = apparent mat permeability factor, $\text{mol/m}^3 \cdot \text{atm} \cdot \text{s}$

P_{amb} = ambient total pressure, atm.

It must be emphasized that Eq. (8) does not represent a strict application of permeability. The geometrical considerations are combined in K . The apparent mat permeability factor is treated as a constant, but the physical properties of the mat and particles will affect its value.

The molar concentration terms can be expressed as partial pressure by applying the ideal gas law, as shown by Eqs. (5) and (6). The time derivative of the molar concentration of water vapor becomes:

$$\frac{dc_w}{dt} = \frac{1}{RT} \frac{dp_w}{dt} - \frac{p_w}{RT^2} \frac{dT}{dt} \quad (9)$$

Substituting Eqs. (8) and (9) into (7), and solving for the time derivative of the partial water vapor pressure yields:

$$\frac{dp_w}{dt} = \frac{dP}{dt} + \frac{(p_w - P)}{T} \frac{dT}{dt} + (1-C) K (P - P_{amb}) RT. \quad (10)$$

The known quantities in Eq. (10) are P and T for $0 \leq t \leq t_{max}$, p_w and C for $t=0$, and P_{amb} and R are constants. K can be calculated using experimental data when the value of p_w is known over a definite time period. The temperature and gas pressure data reported by Kamke and Casey (1988 b) for the core of a mat pressed at 15% moisture content revealed a saturated environment. In this case, the change of the water vapor pressure is equal to the change of the saturated water vapor pressure, which is only a function of temperature. With this information Eq. (10) was solved numerically to obtain K equal to $8.9 \times 10^{-4} \text{ mol/m}^3 \cdot \text{atm} \cdot \text{s}$. This value is used for all the other mats containing the same flake geometry, average mat density and size.

Equation (10) is solved numerically using a backward differencing scheme to obtain the partial water vapor pressure as a function of time. The relative vapor pressure is calculated using the relationship in Eq. (2). The equilibrium moisture content is then estimated from the sorption relationship given by Eq. (1).

With the above analysis the environment conditions surrounding a flake have been defined. These conditions consist of measured temperature and total gas pressure data and estimated relative vapor pressure over the entire press cycle. The next

step is to model the change of temperature and moisture content inside a wood flake as a result of these internal mat conditions.

Heat and mass transfer model

The model used to describe the heat and mass transfer inside of an individual wood flake is one developed by Stanish et al. (1985) and Schajer (1984). The heat and mass transfer process in wood is mathematically described by a set of one-dimensional transport equations (the length and width directions are neglected) that are coupled using an expression of thermodynamic phase equilibrium. The model considers heat transfer via conduction and convection. Mass transfer occurs as a result of gaseous and bound water diffusion, and hydrodynamic flow of gaseous and liquid water. Diffusion of bound water is considered to be driven by a gradient in chemical potential. The bound water concentration is determined at the local temperature using an inverted form of the one-hydrate Hailwood-Horobin model fit to low temperature sorption data (Simpson 1971). The physical properties of the wood are allowed to vary with both space and time. Therefore, any transport equations that are dependent on these properties can vary similarly. The reader is referred to the literature for a more thorough discussion of the model.

Boundary conditions

The boundary conditions of temperature and relative vapor pressure surrounding a flake must be known to apply the heat and mass transfer model. The measured mat data presented by Kamke and Casey (1988 b) was used for this information. Twelve yellow poplar flakeboard mats were pressed in a 61 × 61 cm laboratory hot-press to a nominal density of 750 kg/m³. Two platen temperatures (154° and 190 °C) and initial mat moisture contents (6% and 15%) were used. The panels were bonded with 5% phenol-formaldehyde resin solids with a one-minute press closing time and twelve-minute total press time. Temperature and total gas pressure data were acquired by a computer at face and core locations in each mat. Relative vapor pressure was calculated from the temperature and total gas pressure data as described previously.

Other information required for solving the heat and mass transfer model are the convective heat and mass transfer coefficients that correspond to the surfaces of the flakes within the mat. An estimate of these values will be described in the following discussion.

Results and discussion

Transient EMC conditions

A plot of the measured temperature and calculated relative vapor pressure in the core and the face region of a flakeboard mat pressed at 190 °C, with a 15% moisture content, is shown in Fig. 1. Note the significant increase of the relative vapor pressure

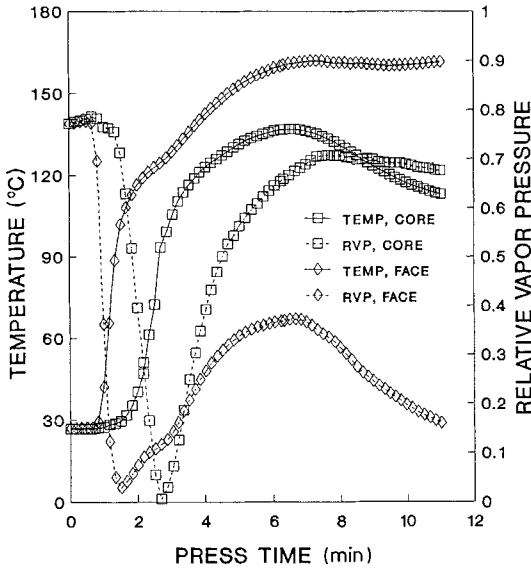


Fig. 1. Measured temperature and predicted relative vapor pressure in the face and core regions of a mat pressed at 190°C and 15% moisture content

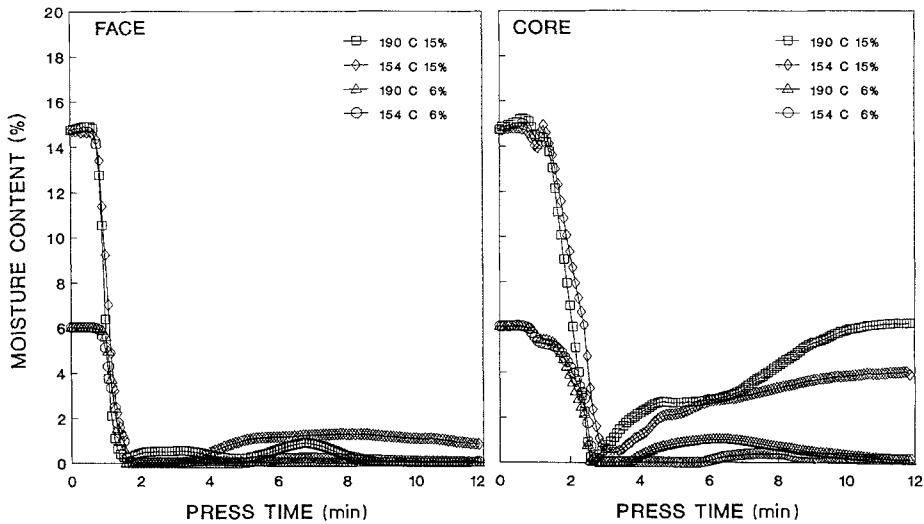


Fig. 2. Predicted equilibrium moisture content based on measured temperature and total gas pressure in the face and core regions of mats pressed under the conditions indicated

in both the face and the core beginning at 1.5 and 2.5 min into the press cycle, respectively. This corresponds to an increase of the total gas pressure, and does not begin until after the initial rise of temperature. When venting begins at 6 min, the relative vapor pressure in the face declines. However, the relative vapor pressure in the core remains at a high level. The temperature in the core declines during the venting period, indicating the presence of a significant amount of water in a con-

densified phase. As the total pressure of the core region is reduced, the latent heat of evaporation results in a net reduction of the temperature.

The transient EMC conditions that occurred at face and core locations in the mats considered are presented in Fig. 2. Initially, the EMC conditions are equal to the initial mat moisture content as imposed by the procedure used to calculate relative vapor pressure. The EMC drops rapidly as the temperature increases in the mat. As the bound water in the wood evaporates and moves into the void spaces between flakes, the relative vapor pressure, and therefore, the EMC conditions increase. This is particularly evident in the core. When venting begins (6 min into the press cycle), the water vapor rapidly dissipates out of the panel, and the total gas pressure drops. The relative vapor pressure and EMC may remain the same, increase, or decrease depending on the amount of water remaining in the wood. It is interesting to note that the EMC of the core in the 190 °C and 15% moisture content mat increases during the venting period. This occurs because the latent heat of evaporation causes a reduction of the temperature while the relative vapor pressure remains approximately constant.

Estimating parameters for the heat and mass transfer model

The use of a mechanistic model to describe the heat and mass transfer in wood requires the knowledge of several physical parameters and some transport coefficients. The physical parameters that must be known include the flake thickness, density, permeability, bound water diffusivity, water vapor diffusivity, and others. Due to the natural variability of wood, these physical parameters will vary from flake to flake. Stanish et al. (1985) presented most of the relationships necessary for estimating these physical parameters. The flake density and thickness can be measured, but these quantities change during the process of hot-pressing. Describing the heat and mass transfer across the boundary of the flake requires a knowledge of convective heat and mass transfer coefficients. Empirical equations are available in the literature that can be used for calculating convective heat and mass transfer coefficients for gas flow through granular beds of material. Using results from the literature all of the physical parameters and transport coefficients can be estimated independent of measurements made in a flakeboard mat during hot-pressing. However, a sensitivity analysis of these parameters and coefficients is required to better understand how they affect the overall solution.

A sensitivity analysis for the model was conducted using the experimental data collected from the twelve yellow poplar flakeboard mats. The initial flake thickness and density were used for the analysis. The dominant parameter was found to be the convective heat transfer coefficient. This result is consistent with the results from the literature on wood particle drying (Kamke, Wilson 1986). Because of the relatively short distance for heat and moisture movement inside of the wood flake, nearly all the resistance occurs at the surface. Therefore, the convective heat transfer coefficient is expected to be the controlling factor.

Figure 3 shows four simulations for predicting the average moisture content of flakes during hot-pressing. Four values for the convective heat transfer coefficient, each differing by an order of magnitude, were used. The average moisture content was

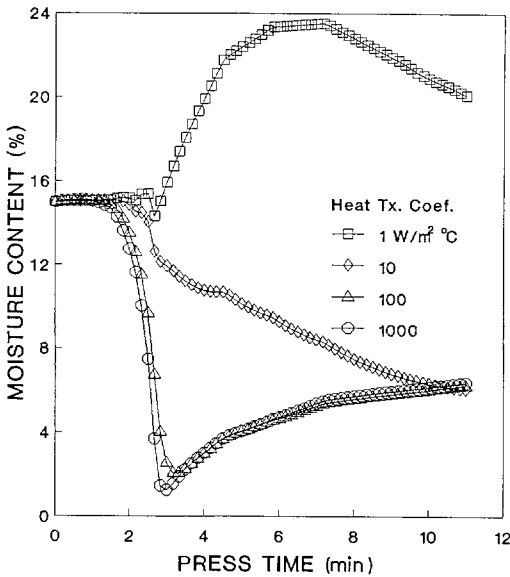


Fig. 3. Predicted average moisture content of a flake in the core of a mat pressed at 190°C and 15% moisture content as a function of the convective heat transfer coefficient

predicted for both a face and core location in the mat (only the core is shown in Fig. 3). As the convective heat transfer coefficient is decreased from a maximum value of 1,000 W/m² K, the predicted moisture content increases. The lowest convective heat transfer coefficient (1 W/m² K) resulted in an unrealistic increase in the predicted moisture content in both the face and core locations. The convective heat transfer coefficients of 100 and 1,000 W/m² K show the expected rapid decrease in the predicted moisture content shortly after the press closes. However, after approximately 3–4 min the moisture content in both the face and the core is predicted to increase. This result is also unrealistic because the total moisture content of the mat must decrease over time. Based on this reasoning, a value for the convective heat transfer coefficient on the order of 10 W/m² K would appear to be appropriate. In this case, the predicted moisture content in the face rapidly decreases at the end of the press closing time and begins a more gradual decline. The predicted moisture content in the core begins to decline at a later time and more gradually.

It is unreasonable to expect that the convective heat transfer coefficient would remain constant during the entire press cycle. The flow of heat due to convection is the result of gas movement through the mat, with this gas being primarily water vapor generated through evaporation. Since the rate of evaporation of moisture from the wood particles will be changing during the press cycle, the rate of gas flow through the mat would also change. Therefore, the convective heat transfer coefficient would not be constant. Nevertheless, for the lack of more information, this analysis assumes a constant convective heat transfer coefficient.

Since the heat and mass transfer model is only applied to an individual flake, there is no balance of heat and mass that is mathematically satisfied over the entire flake mat. The environment data from the flake mats does not identify where water vapor is generated, but only that it is present. As a result, the analysis of temperature and moisture content change in the face and core locations are performed independently.

Toei et al. (1967) developed methods for calculating convective heat transfer coefficients for super-heated steam drying of porous solids. Their experimental data was collected using a fixed-bed of clay and sawdust with a moving stream of steam passing through the bed. Their equation, with the terms regrouped, is:

$$h = 1.95 \left(\frac{GD_p}{\mu} \right)^{0.49} \left(\frac{c\mu}{k} \right)^{0.33} \frac{k}{D_p} \quad (11)$$

where

G = mass gas flow rate ($\text{kg}/\text{m}^2 \text{ s}$)

D_p = equivalent particle diameter (m)

μ = viscosity of the gas (steam = $1.3 \times 10^{-7} \text{ Pa s}$)

c = specific heat of gas (steam = $2,060 \text{ J}/\text{kg } ^\circ\text{C}$)

k = thermal conductivity of gas (steam = $0.025 \text{ W}/\text{m C}$).

In estimating G for the hot-pressing operation, the focus is on the initial 6 min of the pressing cycle where nearly all of the temperature increase occurs. During this time, moisture is driven primarily from the face to the core region of the mat. It is assumed, for the moment, that the gas flow consists entirely of water vapor. For initial and final mat moisture contents of 15% and 6%, respectively, and a cross-sectional area of 0.37 m^2 , the average mass flow rate is estimated as $0.005 \text{ kg}/\text{m}^2 \text{ s}$. D_p was determined for an average flake ($5 \times 1 \times 0.09 \text{ cm}$) using the method of equivalent surface area of a sphere (Perry, Chilton 1973). Using Eq. (11) the value for h is estimated to be $7 \text{ W}/\text{m}^2 \text{ K}$. This value corresponds well to the most reasonable moisture content profile generated using the sensitivity analysis shown in Fig. 3 ($h = 10 \text{ W}/\text{m}^2 \text{ K}$). All subsequent analyses use $h = 10 \text{ W}/\text{m}^2 \text{ K}$.

The flake thickness and density also influence the predictions from the heat and mass transfer model. Because the flakes deform viscoelastically, and transient temperature and moisture gradients exist in the mat, the flakes are likely to continuously deform during much of the pressing cycle (Wolcott et al. 1989). However, fixed physical dimensions must be given for the wood element in the heat and mass transfer model. The results of simulations using the initial and final flake thickness and density are presented in Fig. 4. As shown, there is little difference between the use of the initial or final flake thickness and density. The use of the final flake dimensions is more realistic because the flake must approach the final dimensions at the time the press is closed and much of the stress is relieved. Therefore, the remaining simulations use the final flake dimensions.

Flake moisture content predictions

The heat and mass transfer model predicts that a significant moisture content gradient develops in the flake (Fig. 5). When the internal environment changes slowly, the gradients are small. However, during rapid changes the moisture gradient is significant. Interpretation of this result raises the question whether local thermodynamic equilibrium is an appropriate assumption when the mat is modelled as a continuum. In other words, the flake moisture content is not equivalent to the EMC. The example

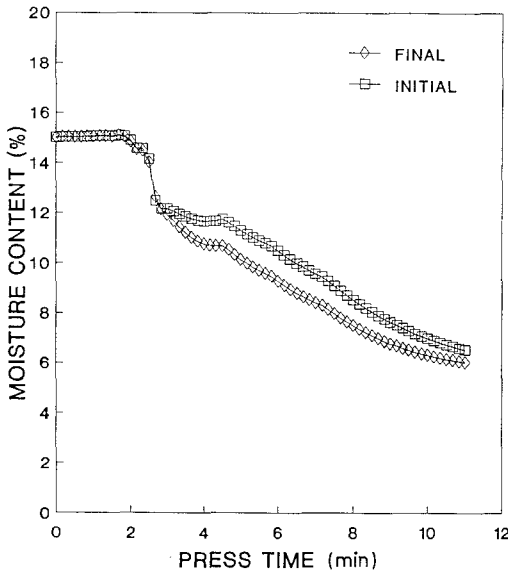


Fig. 4. Predicted average moisture content of a flake in the core of a mat pressed at 190°C and 15% moisture content assuming initial and final flake thickness and density

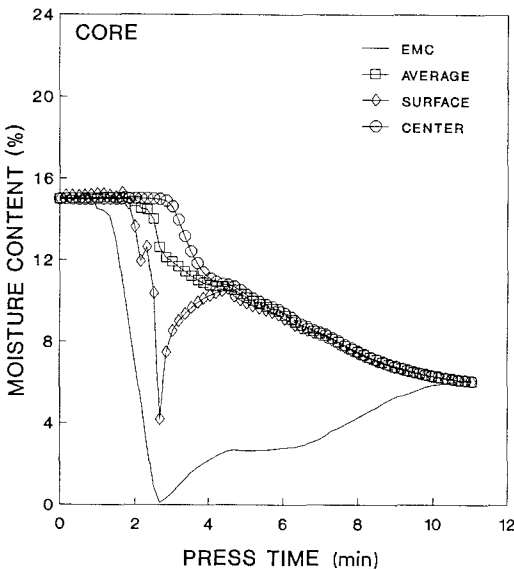


Fig. 5. Predicted equilibrium moisture content and moisture gradient of a flake in the core of a mat pressed at 190°C and 15% moisture content

in Fig. 5 shows that the EMC and flake moisture content are close only at the beginning and end of the press cycle.

As shown in Fig. 6, the flake temperature does not develop a significant gradient. The transport of heat in wood is much more rapid than the transport of moisture. The difference between the measured temperature of the surrounding environment and the flake temperature is indicative of the estimated convective heat transfer coefficient.

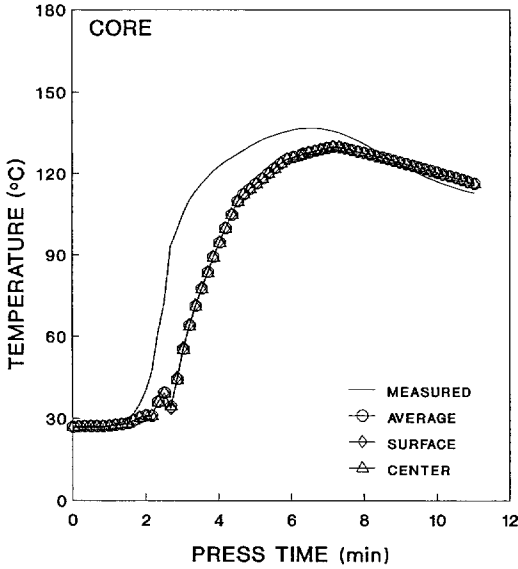


Fig. 6. Measured temperature and predicted temperature gradient of a flake in the core of a mat pressed at 190°C and 15% moisture content

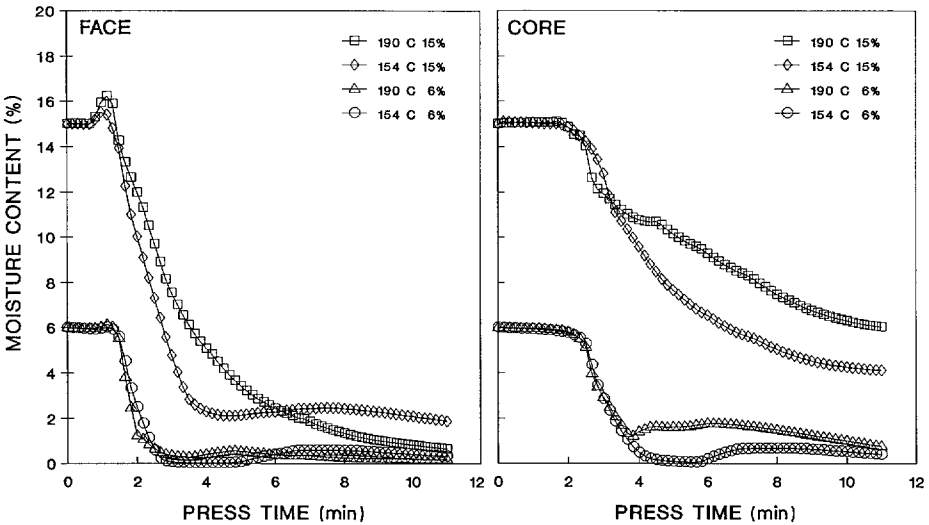


Fig. 7. Predicted average flake moisture content in the face and core regions of mats pressed under the conditions indicated

The predicted average moisture content for the four pressing schedules studied are presented in Fig. 7. This method predicts an initial plateau of moisture content with a rapid decrease beginning after press closure in the face. The decrease of moisture content in the core is delayed up to one minute in these mats, and then begins a more gradual decline. Another plateau may be obtained in the core, followed by a final decrease of moisture content after venting begins at 6 min into the press cycle. It is

interesting to note that condensation is predicted well into the press cycle in the low moisture content mats. This increase corresponds to the increase of total gas pressure in the core. A small peak in moisture content in the face of the high moisture content mats is predicted, beginning when the press is closed. This results from the entrapment of gas in the voids of the face region, and the corresponding increase of total gas pressure. This is a pressure and volume phenomena.

Summary and conclusions

A method has been presented to calculate the relative vapor pressure in the internal environment of a flakeboard mat during hot-pressing. This technique uses measured temperature and gas pressure data from the mat. A mathematical relation for EMC as a function of temperature and relative vapor pressure is used to determine the transient EMC conditions that exist in the mat.

Temperature and moisture content of the wood component are predicted using a fundamental heat and mass transfer model for wood. Use of this method shows that a significant resistance to convective heat transfer at the surface of a flake controls the heat and mass transfer between the wood flake and the internal environment. The temperature and moisture content of the wood component is not in equilibrium with the internal mat environment.

Several assumptions were required to solve the model presented here. While this may limit the quantitative use of the model, the predicted trends are reasonable and do not conflict with the limited experimental data that is available. These results have implications on the development of the vertical density gradient, adhesive bond formation, mat venting, springback, and other panel properties or behavior that depend on wood moisture content and temperature.

References

- Back, E. L. 1987: The bonding mechanism in hardboard manufacture. *Holzforschung* 41: 247–258
- Benjamin, J. R.; Cornell, C. A. 1970: Probability, statistics, and decision for civil engineers. New York: McGraw Hill
- Brady, D. E.; Kamke, F. A. 1988: Effects of hot-pressing parameters on resin penetration. *For. Prod. J.* 38: 63–68
- Chow, S. Z.; Mukai, H. N. 1972: Polymerization of phenolic resin at high vapor pressure. *Wood Sci.* 5: 65–72
- Forest Products Laboratory 1987: Wood handbook: Wood as an engineering material. *Agric. Handb.* 72, p. 3–11. Washington, DC: U.S. Department of Agriculture
- Frantz, J. F. 1961: Fluid-to-particle heat transfer in fluidized beds. *Chem. Engr. Prog.* 57: 35–42
- Geimer, R. L.; Mahoney, R. J.; Loehnertz, S. P.; Meyer, R. W. 1985: Influence of processing-induced damage on strength of flakes and flakeboards. FPL Res. Pap. No. 463. U.S. For. Prod. Lab., Madison, WI
- Harless, P. E.; Wagner, F. G.; Short, P. H.; Seale, R. D.; Mitchell, P. H.; Ladd, D. S. 1987: A model to predict the density profile of particleboard. *Wood Fiber Sci.* 19: 81–92
- Humphrey, P. E. 1979: Fundamental aspects of wood particleboard manufacture. Ph.D. Dissertation. Univ. of Wales, Bangor, Wales, U.K.; 158 p
- Kamke, F. A.; Wilson, J. B. 1986: Computer simulation of a rotary dryer: Part II: Heat and mass transfer. *AIChE J.* 32: 269–275

- Kamke, F. A.; Casey, L. J. 1988 a: Gas pressure and temperature in the mat during flakeboard manufacture. *For. Prod. J.* 38: 41–43
- Kamke, F. A.; Casey, L. J. 1988 b: Fundamentals of flakeboard manufacture: internal mat conditions. *For. Prod. J.* 38: 38–44
- Kayihan, F.; Johnson, J. A. 1983: Heat and moisture movement in wood composite materials during the pressing operation – a simplified model. In: Lewis, R. W.; Morgan, K.; Schrefler, B. A. (Eds.): *Numerical methods in heat transfer*. Vol. 2, New York: Wiley
- Perry, R. H.; Chilton, C. H. 1973: *Chemical engineers' handbook*. 5 Ed. pp. 5–62. New York: McGraw-Hill
- Resch, H.; Hoag, M. L.; Rosen, H. N. 1988: Desorption of yellow poplar in superheated steam. *For. Prod. J.* 38: 13–18
- Simpson, W. T. 1971: Equilibrium moisture content prediction for wood. *For. Prod. J.* 21: 48–49
- Simpson, W. T. 1973: Predicting equilibrium moisture content of wood by mathematical models. *Wood Fiber* 5: 41–49
- Simpson, W. T.; Rosen, H. N. 1981: Equilibrium moisture content of wood at high temperatures. *Wood Fiber* 13: 150–158
- Schajer, G. S. 1984: DRYRUN, One dimensional wood drying computer program. Solid Wood Research and Development, Weyerhaeuser Company, Tacoma, WA
- Snedecor, G. W.; Cochran, W. G. 1967: *Statistical methods*. 6 Ed., p. 432. Ames, IA: Iowa State University Press
- Stanish, M. A.; Schajer, G. S.; Kayihan, F. 1985: Mathematical models of wood drying from heat and mass transfer fundamentals. In: Toei, R.; Mujumdar, A. S. (Eds.): *Drying '85*. pp. 360–367. New York: Hemisphere
- Strickler, M. D. 1959: Properties of Douglas-fir flakeboard. *For. Prod. J.* 7: 203–215
- Toei, R.; Okazaki, M.; Kimura, M.; Ueda, H. 1967: Heat transfer coefficients on the super-heated steam drying of porous solids. *Kagaku Kogaku* 5: 139–141
- Treybal, R. E. 1980: *Mass-transfer operations*. pp. 202. New York: McGraw-Hill
- Wolcott, M. P.; Kamke, F. A.; Dillard, D. A. 1989: Fundamentals of flakeboard manufacture: viscoelastic behavior of the wood component. *Wood Fiber Sci.* (in press)

(Received June 2, 1989)

F. A. Kamke
Dept. Wood Science and Forest Products
Brooks Forest Products Center
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061-0503
USA

M. P. Wolcott
Wood Science
West Virginia University
Morgantown, WV 26506
USA