

HEAT AND MASS TRANSFER IN WOOD COMPOSITE PANELS DURING HOT-PRESSING: PART I. A PHYSICAL-MATHEMATICAL MODEL

Chunping Dai[†]

Group Leader—Composites Group

and

Changming Yu

Visiting Professor
Forintek Canada Corp.
2665 East Mall, Vancouver, BC
V6T 1W5

(Received November 2003)

ABSTRACT

A theoretical model for heat and moisture transfer in wood composite mats during hot-pressing is developed based on the basic principles of mass conservation, momentum of gas flow, energy conservation, and resin curing kinetics. The model provides a mathematical description of the coupled physical phenomenon in hot-pressing process as a closure problem in which fifteen governing equations are rigorously derived to solve fifteen unknown variables of mat environmental conditions. These variables, including mat temperature, gas pressure, and moisture content are linked to basic material properties such as mat density, thermal conductivity, and permeability. Initial and boundary conditions for solving the governing equations are also discussed.

Keywords: Wood composites, hot pressing, heat and mass transfer, modeling.

INTRODUCTION

Wood composites are usually manufactured by consolidating mats of resinated wood furnishes under heat and pressure for a certain duration of time. The combination of heat, pressure, and time allows the resin to cure while wood furnishes are held in their intimate contact positions. Upon press opening, the cured resin forms bonds between wood elements and therefore integrated products. Heating is not only necessary to shorten the resin curing time, but also soften wood material, allowing a high degree of mat densification to be achieved using minimum mat pressure. The densities of the pressed mats or composite panels are usually nonuniform, namely, higher density in the surface layers and lower density in the core. This well-known vertical density profile is resultant of the temporal and spatial interactions

between mat pressure and heat and mass transfer. Heat and mass transfer is without doubt of great importance in governing the productivity and the physical and mechanical properties of the final composite products.

While improving the fundamental understanding of the composite manufacturing process, this publication series will first report a mathematical model of heat and mass transfer based on the physics of hot-pressing. In Part 2, a fundamental model will be developed to predict the variations of void volume and mat permeability during pressing. In Part 3, the model predictions will be compared with experimental observations and typical predicted results will be discussed.

BACKGROUND

Because of its critical importance, heat and mass transfer during hot-pressing has been ex-

[†] Member of SWST.

tensively investigated. As such, a large body of knowledge has been accumulated. While most researchers employed experimental approaches as reviewed earlier by Bolton and Humphrey (1988) and recently reported by (Winistorfer et al. 1999), others attempted to model the physical processes during hot pressing (Harless et al. 1987; Humphrey and Bolton 1989; Carvalho and Costa 1998; Haselein 1998; Thomen 2000; Dai et al. 2000; Zombori et al. 2003). Humphrey and Bolton (1989) were among the first to study the heat and mass transfer process for particleboard during hot-pressing. While analyzing the mechanisms of heat and mass transfer, a model was introduced to predict the environmental conditions inside the particleboard mats during hot-pressing (Humphrey and Bolton 1989). In their successive publications, typical predictive results were presented and analyzed (Bolton et al. 1989a,b). Their model significantly improved the understanding of the hot-pressing process and at the same time revealed the complexity of the subject and the need for more research.

The research work of Haselein (1998), Thomen (2000), Thomen and Humphrey (2003) was a direct extension and modification of the original model of Humphrey and Bolton (1989), while similar models were also developed by Carvalho and Costa (1998) and Zombori et al. (2003). To date, the model for heat and mass transfer in the composites hot-pressing process has yet to be fully established, largely because of the following reasons:

1. *The Coupling and Interactive Nature of the Hot-Pressing Process.* When a composite mat is pressed under heat and pressure, the relationship between the pressure and layered mat density is governed by a highly nonlinear stress-strain compression process (Dai and Steiner 1993; Dai 2001; Lang and Wolcott 1996) and the mat temperature and moisture content flow is a coupled heat and mass transfer process (Humphrey and Bolton 1989; Zombori et al. 2003). Both the mechanical deformation process and the heat and mass transfer process interact with each other. Whereas heat and moisture soften the

material and thus facilitate mat densification, the change in mat density can significantly affect the heat conduction and moisture flow. Since wood composite mats are hydrophilic and porous, the heat transfer inevitably causes the flow of moisture or vice versa. In addition, the curing of resin, while governed by the laws of chemical reactions, can result in release or absorption of heat and water, which may in turn affect the heat and mass transfer process. The bonds formed between the resin and wood elements also have an effect on the mat deformation behavior particularly springback upon and after pressing (Dai et al. 2000).

2. *Inadequate Knowledge of the Physical Properties of Wood Composite Mats during Pressing.* Despite efforts by von Haas (1998) and others (Hata 1993 and Hata et al. 1993), many basic material properties including mat conductivity and permeability have not been accurately defined. The relationships between these material properties and wood-element geometry are almost completely lacking. Most of the experiments have been reported using tests of pre-pressed boards under isothermal heat transfer and steady mass flow, which may be inadequate to simulate the transient dynamics of mat structure and environmental conditions during hot-pressing. The difficulties in defining the material processing properties also lie in the fact that wood composite mats are not physically integrated for handling during testing and they are usually structurally heterogeneous, meaning that the properties may be orientation- and furnish-dependent. Special testing devices are usually needed to control temperature up to 220°C and to seal the induced steam inside the testing materials and to prevent the material from thermal degradation.

The heat and mass transfer model presented in this paper is a three-dimensional (3-D) model as opposed to a two-dimensional (2-D) model (Zombori et al. 2003) or a cylindrical model (Humphrey and Bolton 1989). Our model also uses a more rigorous approach to elaborating the

heat and mass transfer mechanisms and to explicitly establishing all the main variables and their governing equations.

MODEL DEVELOPMENT

Realizing its complex and coupling nature, a model of heat and mass transfer is presented in this paper as a coupled closure problem. The concept of a closure problem is used here to ensure the completeness of the model, because it requires that the number of equations is equal to that of the unknowns to reach mathematically unique solutions. In deriving the model, several physics principles have been employed including the law of mass and energy conservation, momentum law of gas flow, thermodynamics, resin curing kinetics, and mechanics of mat consolidation. Besides the mechanics of mat consolidation, which addresses the mat deformation and

density variation, all the other principles are directly related to deriving the heat and mass transfer model and therefore discussed in this paper. Figure 1 shows the various model components and their relationships. The heart of the model is based on the law of mass and energy conservation for predicting mat environmental conditions such as temperature and moisture content. While both heat conduction and convection are considered to calculate mat temperature, the momentum law of gas flow and thermodynamics relations are needed to determine the gas flow velocity and pressure. Resin curing can also contribute to the heat and mass transfer through heat generation or absorption (water generation or consumption may also result from curing). While following the physics principles, the mat environmental conditions are externally controlled by press operating parameters and internally by mat properties.

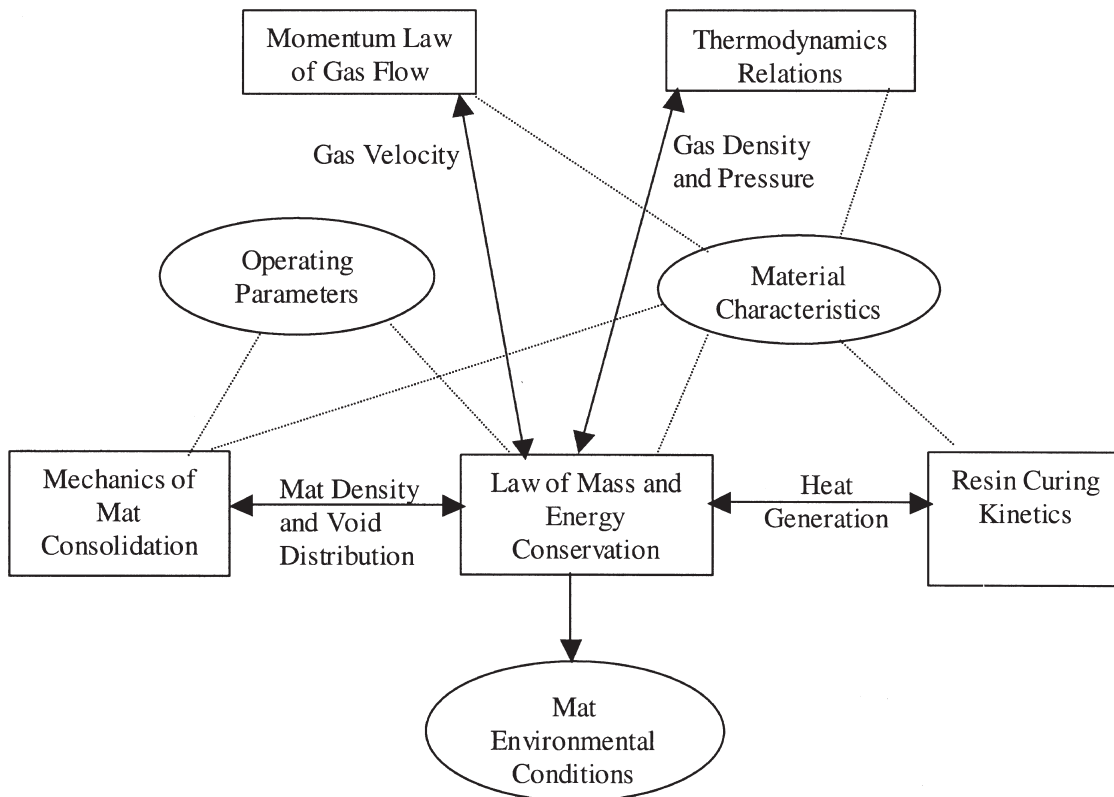


FIG. 1. Flow chart of the heat and mass transfer model.

General hypotheses and treatments

A composite mat is viewed as a rectangular volume having fixed length L and width W and variable thickness ZH in the time domain. Because of the symmetry with respect to the heat and mass flow along the X and Y axis, calculations are only needed for one fourth of the mat (Fig. 2).

In order to model the mass flow and continuous distribution of the mat environmental variables, the mat is considered as both a porous and a continuum material. As a porous material, a mat consists of media of solid phase and gas phase. The solid medium is made of wood elements containing water. The moisture content in wood elements is mostly bound water in the case of wood composite pressing as it is usually significantly below fiber saturation point. Hence the evaporation involves latent heat both from bound water to free water and from free water to vapor. The latter also applies for calculating heat of condensation.

Gas is a mixture of air and vapor that is assumed to exist only inside the voids between and within wood elements. Gas flow is assumed to be caused by the gradients of total gas pressure. Diffusion of gas and liquid water are neglected compared to the flow.

The assumption of the mat being a continuum allows for the continuous existence of gas and solid phase media without boundaries. All variables including mat temperature, moisture content, and gas pressure are continuous within the mat.

Another important assumption is that local isothermal sorptive equilibrium exists between

mat moisture content, gas relative humidity, and temperature. Air and vapor as well as their mixture are viewed as ideal gases and therefore follow the ideal gas equation.

Governing equations

The model involves five major aspects: mass conservation, momentum of gas flow, energy conservation, thermodynamics, and resin curing kinetics.

Mass conservation.—Assume there is no resin flow inside the mat during pressing. The mass mainly includes solids (wood elements) and gas (air and steam). The mat density ρ_{mat} at any position is a total of densities of solids (wood elements including water) and gas media, or:

$$\rho_{mat}(x, y, z, \tau) = (1 - \varepsilon(x, y, z, \tau))\rho_s(x, y, z, \tau) + \varepsilon(x, y, z, \tau)\rho_g(x, y, z, \tau) \quad (1a)$$

Here, ρ_s and ρ_g are respectively the density of solid phase and gas phase media [kg/m^3], and ε is the void fraction of the mat. They are dependent upon location x , y , and z and time τ . Deriving the above equation over time, we have:

$$\frac{d\rho_{mat}}{d\tau} = \frac{d(1 - \varepsilon)\rho_s}{d\tau} + \frac{d\varepsilon\rho_g}{d\tau} \quad (1b)$$

The above equation shows that the mass variation per time per volume in the mat equals that of solid phase and gas phase mass over the same time and volume. The solid phase media mass variation per time per volume in the mat as expressed in the above equation can be extended to:

$$\frac{d(1 - \varepsilon)\rho_s}{d\tau} = (1 - \varepsilon)\frac{d\rho_s}{d\tau} + \rho_s\frac{d(1 - \varepsilon)}{d\tau} \quad (1c)$$

Equation (1) shows that the variation of solid phase media mass per volume is caused by two components: the variation of density of solid media and the variation of porosity in the mat. The porosity variation will be discussed in future papers.

The solid phase media is the wood elements which consists of dry wood and water. Its den-

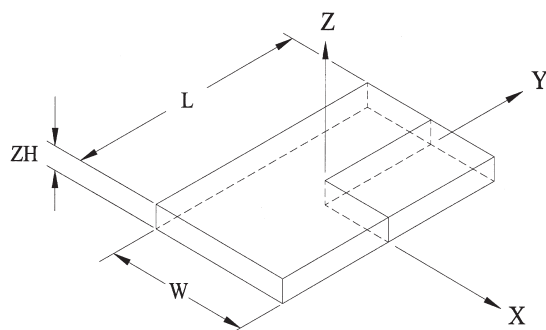


FIG. 2. One fourth of a mat and coordinate system.

sity is the sum of the dry wood and water volume density, or:

$$\rho_s = \rho_{dry} + \rho_{dry}MC \quad (1d)$$

Here MC is the moisture content based on oven-dry weight.

Deriving Eq. (1d), we have:

$$\frac{d\rho_s}{d\tau} = \frac{d\rho_{dry}}{d\tau} + \frac{d\rho_{dry}MC}{d\tau} \quad (1e)$$

Equation (1e) reveals that the density variation of solid phase media is further caused by the variation of dry wood density which is governed by mat deformation during pressing, and the change of moisture due to evaporation or condensation, which can be further expressed as:

$$-\frac{d\rho_{dry}MC}{d\tau} = \dot{E}_{evap} \quad (1)$$

Here, \dot{E}_{evap} is the evaporation rate. It denotes the mass generation per time and per volume [kg/m³*sec.].

Equation (1) can be considered as the governing equation for moisture content MC if \dot{E}_{evap} is known. It implies that the loss (or gain) of water mass in solid media equals the increment (or reduction) of vapor mass in gas media.

The gas mass in the mat is a mixture of air and water vapor inside the voids. Other gas components such as volatile compounds are neglected. The density of the gas ρ_g is thus the sum of air volume density ρ_a and vapor volume density ρ_v , or:

$$\rho_g = \rho_a + \rho_v \quad (2)$$

Because the air escapes mainly through the mat edges during pressing, the air density inside the mat is assumed to vary only in the lateral directions (x, y):

$$\frac{\partial \epsilon \rho_a}{\partial \tau} + \frac{\partial \rho_a u_{xg}}{\partial x} + \frac{\partial \rho_a u_{yg}}{\partial y} = 0 \quad (3)$$

Here, u_{xg} and u_{yg} are the gas flow velocity along x-axis and y-axis, respectively. Equation (3) can be rearranged as:

$$-\frac{\partial \epsilon \rho_a}{\partial \tau} = \frac{\partial \rho_a u_{xg}}{\partial x} + \frac{\partial \rho_a u_{yg}}{\partial y}$$

which means that the reduction of air mass in a unit volume and time equals the mass flow to the surrounding areas. Equation (3) is the governing equation for air density ρ_a which can be determined if u_{xg} , u_{yg} , and ϵ are known.

Unlike the air flow, the flow of vapor is assumed to occur in all three directions (x, y, z) and the mass of vapor at a given void volume can also be generated from moisture contained in the surrounding wood elements, as long as their temperature is above the evaporation point. Assuming the vapor velocity is the same as air or gas velocity, the mass conservation of vapor can then be written as:

$$\frac{\partial \epsilon \rho_v}{\partial \tau} + \frac{\partial \rho_v u_{xg}}{\partial x} + \frac{\partial \rho_v u_{yg}}{\partial y} + \frac{\partial \rho_v u_{zg}}{\partial z} = \dot{E}_{evap} \quad (4)$$

or

$$\frac{\partial \epsilon \rho_v}{\partial \tau} = \frac{\partial \rho_v u_{xg}}{\partial x} - \frac{\partial \rho_v u_{yg}}{\partial y} - \frac{\partial \rho_v u_{zg}}{\partial z} + \frac{\dot{E}_{evap}}{\dot{E}_{evap}}$$

Here, u_{xg} , u_{yg} , and u_{zg} are the effective gas velocities in x, y and z directions, respectively. They can be solved by the gas momentum equations to be discussed in the following sections. The volume density of vapor ρ_v can be determined based on the thermodynamics relations. As such, Eq. (4) can be considered as the governing equation for vapor evaporation rate \dot{E}_{evap} .

Momentum of gas flow.—The velocities of gas flow inside the mat obey the gas momentum law for porous media, i.e., the well-known Darcy's law:

$$u_{xg} = -\frac{K_x}{\mu} \frac{dP_g}{dx} \quad (5)$$

$$u_{yg} = -\frac{K_y}{\mu} \frac{dP_g}{dy} \quad (6)$$

$$u_{zg} = -\frac{K_z}{\mu} \frac{dP_g}{dz} \quad (7)$$

Here, K_x , K_y , and K_z , are permeability [m^2] along the x, y (horizontal), and z (vertical) directions, respectively. They are governed by the void spaces between wood elements, which are further dependent upon the local mat density and the spatial arrangement between the elements. Parameter μ is the dynamic viscosity [$\text{Pa}\cdot\text{sec.}$] of gas (water vapor and air) which varies with the local mat temperature. The forementioned parameters are usually determined by experimentation. Parameter P_g is the gas pressure [Pa], which is governed by the thermodynamics relation to be discussed in the following section. Given that the permeability, gas viscosity, and pressure are known, Eqs. (5), (6), and (7) can be considered as the governing equations for the gas flow velocities u_{xg} , u_{yg} and u_{zg} .

So far, we have seven equations (Eqs. 1–7) for nine unknowns: MC, \dot{E}_{evap} , u_{xg} , u_{yg} , u_{zg} , ρ_a , ρ_v , ρ_g , and P_g . Therefore, more equations are needed.

Energy conservation

Energy conservation for solid phase media (wood elements).—Wood elements in the mat obtain heat through heat conduction and to a less extent, energy generation from resin curing. By the conservation law, the energy obtained by wood elements manifests itself in wood temperature increase, moisture evaporation, and heat exchange between wood and gas in the voids. Specifically, the energy conservation for wood elements can then be expressed using the following partial differential equation:

$$\begin{aligned} & \frac{\partial(1-\varepsilon)\rho_s C_s T_s}{\partial \tau} + \dot{E}_{\text{evap}} \times H_{fg} + hF(T_s - T_g) \\ &= \frac{\partial}{\partial x} \left((1-\varepsilon)k_{sx} \frac{\partial T_s}{\partial x} \right) + \frac{\partial}{\partial y} \left((1-\varepsilon)k_{sy} \frac{\partial T_s}{\partial y} \right) \\ &+ \frac{\partial}{\partial z} \left((1-\varepsilon)k_{sz} \frac{\partial T_s}{\partial z} \right) + Q_r \end{aligned} \quad (8a)$$

Here, C_s is specific heat of solid phase media [$\text{J}/(\text{kg}\cdot\text{K})$], T_s and T_g respectively, the solid and gas phase temperature [$^{\circ}\text{C}$], H_{fg} the evaporation (or condensation) latent heat [J/kg], h the con-

vection heat transfer coefficient [$\text{W}/(\text{m}^2\cdot\text{K})$], and F the heat exchange area per volume [m^2/m^3] between the solid phase and gas phase media in the mat. Parameters k_{sx} , k_{sy} , and k_{sz} are, respectively, the solid phase thermal conductivity [$\text{W}/(\text{m}\cdot\text{K})$] along the x, y, and z directions. Parameter Q_r is the heat generation rate [$\text{J}/(\text{m}^3\cdot\text{sec.})$] during resin curing (see the resin curing kinetics model). In fact, Eq. (8a) is an energy balance for a control volume with boundaries that separate the wood element from the surrounding voids.

Energy conservation for gas phase media (mixture of air and water vapor).—For the gas phase media, the heat energy comes from heat conduction and convection as well as exchange from the solid media. The energy causes the gas temperature to increase and the temperature of the freshly evaporated vapor to reach that of the gas. The energy conservation for the gas phase media can then be expressed with the following partial differential equation:

$$\begin{aligned} & \frac{\partial \varepsilon \rho_g C_g T_g}{\partial \tau} + C_v (T_g - T_s) \dot{E}_{\text{evap}} = \frac{\partial}{\partial x} \left(\varepsilon k_g \frac{\partial T_g}{\partial x} \right) \\ &+ \frac{\partial}{\partial y} \left(\varepsilon k_g \frac{\partial T_g}{\partial y} \right) + \frac{\partial}{\partial z} \left(\varepsilon k_g \frac{\partial T_g}{\partial z} \right) - \frac{\partial \rho_g C_g u_{xg} T_g}{\partial x} \\ &- \frac{\partial \rho_g C_g u_{yg} T_g}{\partial y} - \frac{\partial \rho_g C_g u_{zg} T_g}{\partial z} + hF(T_s - T_g) \end{aligned} \quad (8b)$$

Here, C_g and C_v are, respectively, the specific heat of gas (mixture of air and vapor) and vapor, and k_g the thermal conductivity of gas.

So far, the energy conservation has been analyzed by treating gas and wood elements as separate media. For composite mats of wood elements such as strands, particles, and fibers, a temperature difference may well exist between the gas and wood elements during the dynamic hot-pressing operations. Such a treatment may be justified specially in analyzing heat and mass transfer of strandboard mats where wood elements are usually larger in dimensions than particles and fibers and/or for steam injection pressing in which external steam is rapidly injected to heat relatively cold mats. For mats of particles and fibers, the temperatures of solid

phase media T_s and gas T_g may be assumed to be identical or the mat temperature T_{mat} in order to simplify the mathematical solution. That is:

$$T_s = T_g = T_{mat} \quad (8c)$$

The above assumption further implies that no heat exchange takes place between the gas and solid phase media. Combining Eqs. (8a) with (8b) and (8c) yields:

$$\begin{aligned} & \frac{\partial \rho_{mat} C_{mat} T_{mat}}{\partial \tau} + \dot{E}_{evap} \times H_{fg} \\ &= \frac{\partial}{\partial x} \left(k_{mat,x} \frac{\partial T_{mat}}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_{mat,y} \frac{\partial T_{mat}}{\partial x_y} \right) \\ &+ \frac{\partial}{\partial z} \left(k_{mat,z} \frac{\partial T_{mat}}{\partial z} \right) - \frac{\partial \rho_g C_g u_{xg} T_{mat}}{\partial x} \\ &- \frac{\partial \rho_g C_g u_{yg} T_{mat}}{\partial y} - \frac{\partial \rho_g C_g u_{zg} T_{mat}}{\partial z} + Q_r \end{aligned} \quad (8)$$

Equation (8) is the governing equation for mat temperature T_{mat} . Here, $\rho_{mat} C_{mat}$ is the mat heat capacity [$J/m^3 \cdot K$] which equals the weighted average of heat capacity of solid and gas phase media, or:

$$\rho_{mat} C_{mat} = (1 - \epsilon) \rho_s C_s + \epsilon \rho_g C_g \quad (8d)$$

According to Eq. (1d), $\rho_{mat} C_{mat}$ depends further on mat moisture content, or:

$$\rho_{mat} C_{mat} = (1 - \epsilon)(1 + MC) \rho_{dry} C_s + \epsilon \rho_g C_g \quad (8e)$$

Also in Eq. (8), mat thermal conductivity $k_{mat,x}$, $k_{mat,y}$, and $k_{mat,z}$ are defined as the weighted average of their respective solid phase conductivity and gas conductivity, or:

$$\begin{aligned} & k_{mat,x} + (1 - \epsilon)k_{sx} + \epsilon k_g \\ & k_{mat,y} + (1 - \epsilon)k_{sy} + \epsilon k_g \\ & k_{mat,z} + (1 - \epsilon)k_{sz} + \epsilon k_g \end{aligned} \quad (8f)$$

So far ten unknown variables (MC , T_{mat} , \dot{E}_{evap} , u_{xg} , u_{yg} , u_{zg} , ρ_w , ρ_g , ρ_v , and P_g) are introduced in eight independent equations. Two more equations are therefore needed to warrant mathemati-

cally unique solutions. The two supplemental equations can be obtained from the following thermodynamics relations. It should be noted that during the derivation, some new dependent variables and therefore corresponding equations will be introduced.

Thermodynamics relations

Pressure and relative humidity of gas mixture.—According to Dalton's law, the pressure of a gas mixture equals the total of partial pressure of its constituents. In the present case, the gas pressure should be the sum of the partial pressure of air and water vapor, i.e.

$$P_g = P_a + P_v \quad (9)$$

Equation (9) can be viewed as the ideal governing equation for gas pressure P_g .

Further according to the state equation of perfect gas, air partial pressure P_a and volume density ρ_a are governed by the perfect gas equation:

$$P_a = \frac{\rho_a R T_{mat}}{M_{w_a}} \quad (10)$$

Here, R is the universal gas content [$8.314 J/mol \cdot K$] and M_{w_a} the air molecular weight [$28.97 g/mol$].

Similarly, the relationship between vapor pressure P_v and its density ρ_v follows:

$$\rho_v = \frac{P_v M_{w_v}}{R T_{mat}} \quad (11)$$

Equations (10) and (11) can be viewed as the governing equations for air partial pressure P_a and vapor volume density ρ_v , respectively.

According to the definition of relative humidity of wet air RH , vapor pressure P_v can be expressed by:

$$P_v = RH * P_{sat} \quad (12)$$

Here, P_{sat} is the saturated vapor pressure [Pa] which depends only on air, or in this case, mat temperature T_{mat} . Their relationship is normally given in a standard steam table, or can be described in the following equation (Siau 1995):

$$P_{sat} = \exp\left(53.421 - \frac{6516.3}{T_{mat}} - 4.125 \ln T_{mat}\right) \quad (13)$$

Sorption isotherm relationships.—Due to its hygroscopic nature, wood exhibits adsorptive or desorptive behavior under changing environmental conditions, i.e., relative humidity and temperature. While the relationships between equilibrium moisture content (EMC) and relative humidity (RH) are well documented for temperature under 100°C (e.g. Simpson 1973 and Siau 1995), very little information has been reported concerning the high temperature relationships (Kauman 1956; Lenth and Kamke 2001). Typical hot-pressing temperatures for wood composites vary from 150 to 220°C. Another complicating factor is that local equilibrium may not exist during the transient hot-pressing processes, especially for mats of larger wood elements such as OSB strands. Unfortunately, knowledge of the transient relationship between wood moisture and environmental conditions is presently lacking.

Assuming local equilibrium, the relationship between mat moisture content, relative humidity, and temperature can be obtained based on Gibbs free energy concept (Nelson 1983 and Wu 1999):

$$RH = \exp\left(-\frac{Mw_v}{RT} \exp\left[\ln(\Delta G_0) \left(1.0 - \frac{MC}{MC_v}\right)\right]\right) \quad (14)$$

Here, Mw_v is the molecular weight of water [18.02g/mol], R the universal gas constant, T the absolute temperature of the mat, ΔG_0 Gibbs free energy [J/kg] per unit mass of absorbed water as RH approaches zero, and MC_v a material constant which is approximately equal to the equilibrium moisture content under desorption. Generally speaking, MC_v decreases with increase in temperature (Nelson 1983).

Resin curing kinetics

The resin contained in the mat is partially or completely cured under hot-pressing. The degree of resin cure is the ratio of the mass of cured

resin to the initial mass of uncured resin. The curing process of resin can be expressed as follows:

$$\frac{d\alpha}{d\tau} = K_r(1-\alpha)^n \quad (15a)$$

Here, α is the degree of resin cure (obviously, $\alpha=0$ at time $\tau=0$), $\frac{d\alpha}{d\tau}$ is the resin curing rate, n is the order of the chemical reaction, and K_r is the chemical reaction constant, which can be described by the Arrhenius equation, or:

$$K_r = Ae^{\frac{\Delta E}{RT}} \quad (15b)$$

Here, A is the collision factor [1/sec] and ΔE is the activation energy [J/mol] which can be obtained through experiments and R is the universal gas constant. Combining Eq. (15b) with Eq. (15a) yields:

$$\frac{d\alpha}{d\tau} = Ae^{\frac{\Delta E}{RT}}(1-\alpha)^n \quad (15)$$

The heat generation rate Q_r in Eq. (8) during resin curing can be calculated as following:

$$Q_r = M_{resin} \frac{d\alpha}{d\tau} H_r \quad (15c)$$

Here, H_r is the curing latent heat [J/kg]. M_{resin} is the resin mass per mat volume.

So far, fifteen equations (Eqs. 1–15) have been presented for fifteen unknown variables (MC , T_{mat} , \dot{E}_{evap} , u_{xg} , u_{yg} , u_{zg} , ρ_w , ρ_v , ρ_g , P_w , P_v , P_g , P_{sat} , RH , Q_r). In other words, a coupled closure problem for heat and moisture transfer in composite mats under hot-pressing has been mathematically developed. To solve these equations, one must define the special conditions with respect to time and space.

The variables appearing in the governing equations are classified and are summarized in Tables 1–3. Table 1 contains the spatial and time variables which are independent. Table 2 tabulates all the state variables describing the internal mat environmental conditions. They are dependent variables that can be solved from their cor-

TABLE 1. *Spatial and time variables (Independent variables)*

Time	τ
Position	x, y, z

responding governing equations. Variables listed in Table 3 are characteristic of material properties including thermal conductivity, permeability, and specific heat. Most of these properties are obtained through experimentation.

Special conditions

Initial conditions.—Initial values of all the fifteen state variables are summarized as follows:

- Initial mat temperature $T_{mat,o}$ should be the ambient temperature (e.g., 20°C);

- Initial moisture content MC should be specified before pressing. It usually varies between layers;
- Initial pressure of saturated water vapor depends on initial mat temperature, or $P_{sat,o} = f(T_{mat,o})$. It can be obtained from Eq. (13);
- Initial relative humidity depends on both mat temperature and moisture content, or $RH_0 = f(T_{mat,o}, MC_{mat,o})$. It can be obtained from Eq. (14);
- Initial pressure of water vapor: $P_{v,o} = RH_0 P_{sat,o}$
- Initial air pressure $P_{a,o}$ is the atmospheric pressure, or 10^5 Pa
- Initial pressure of the gas mixture: $P_{g,o} = P_{a,o} + P_{v,o}$
- Initial gas flow velocities: $u_{xg,o} = 0$, $u_{yg,o} = 0$, $u_{zg,o} = 0$,
- Initial density of water vapor: $\rho_{v,o} = \frac{P_{v,o} M_{w_v}}{RT_{mat,o}}$

TABLE 2. *State and other variables (Dependent variables).*

Variables		Governing equations
Mat temperature	T_{mat}	(8)
Saturation vapor pressure	P_{sat}	(13)
Air, vapor, and gas pressure in mat	P_a , P_v , and P_g	(10), (12), and (9)
Air, vapor, and gas density in mat	ρ_a , ρ_v , and ρ_g	(3), (11), and (2)
Velocity of gas flow along x, y, and z direction	u_{xg} , u_{yg} , and u_{zg}	(5), (6), and (7)
Relative humidity	RH	(14)
Evaporation rate	\dot{E}_{evap}	(4)
Moisture content in mat	MC	(1)
Degree of resin curing	α	(15)

TABLE 3. *Material characteristic properties (Parametric variables).*

Properties		Corresponding equations
Porosity	ε	(1)
Oven-dry, wood density	ρ_{dry}	(1)
Permeability	K_x , K_y , and K_z	(5), (6), and (7)
Dynamic viscosity of gas	μ	(5), (6), and (7)
Latent heat	H_{fg}	(8)
Thermal conductivity	$k_{mat,x}$, $k_{mat,y}$, and $k_{mat,z}$	(8)
Specific heat of gas	C_g	(8)
Specific heat of wood	C_s	(8)
Molecular weight of air and water	M_{w_a} and M_{w_v}	(10) and (11)
Universal gas constant	R	(10), (11), (14) and (15)
Activation energy of resin curing	ΔE	(15)
Collision factor	A	(15)
Resin curing latent heat	H_r	(15)
Heat generation rate	Q_r	(15)

- Initial density of air: $P \rho_{a,o} = \frac{P_{a,o} M w_a}{R T_{mat,o}}$
- Initial density of the gas mixture: $\rho_{g,o} = \rho_{a,o} + \rho_{v,o}$
- Initial evaporation rate: $\dot{E}_{evap} = 0$.
- Initial degree of resin cure: $\alpha_o = 0$

Boundary conditions.—Since the model only calculates one quarter of a full mat (Fig.2), the geometric boundaries are defined by:

$$0 \leq x \leq W/2, 0 \leq y \leq L/2 \text{ and } 0 \leq z \leq ZH \quad (16)$$

Here, W and L are the mat width and length, respectively. They are normally given by the dimensions of final products. The mat thickness ZH and its variation with time depend on mat pressure, mechanical properties of the mat, and heat and moisture content transfer inside the mat. The solutions to ZH , \mathcal{E} , and ρ_{dry} are given from the mat consolidation model, which will be discussed in future publications.

When it comes to defining their values at the boundaries, the fifteen variables (Table 2) can be classified into three categories. The first group includes pressure and density of vapor and gas mixture (Eqs. 2, 9, 10, 11, 12), saturation pressure of vapor with respect to local temperature (Eq. 13) and relative humidity (Eq. 14). Their governing equations are algebraic relationships and therefore their values should be defined if their dependent variables are known. The solution of variable \dot{E}_{evap} , (Eq. 4) does not require boundary conditions either.

In the second group, two variables—moisture content and degree of resin cure, are governed by ordinary differential equations with respect to time (Eqs. 1 and 15). No boundary conditions are needed for solving the equations.

In the third group, five variables are governed by five partial differential equations with respect to space variables. They are gas flow velocities: u_{xg}, u_{yg}, u_{zg} (Eqs. 5, 6, 7), air density ρ_a , (Eq. 3), and mat temperature T_{mat} (Eq. 8). Their boundary conditions are:

$$u_{xg} = 0 \text{ at } x = 0 \quad (17a)$$

and

$$u_{yg} = 0 \text{ at } y = 0 \quad (17b)$$

The values of u_{xg} at $x=W/2$ and u_{yg} at $y=L/2$ are given by solving Eqs. (5) and (6) with the surrounding air being at atmospheric pressure.

Regarding the gas flow velocity in z direction,

$$u_{zg} = 0 \text{ at } z = 0 \text{ and } z = ZH, \quad (17c)$$

if the top and bottom platens are in complete contact with the mat.

Or,

$$u_{zg} = -\frac{K_z}{\mu} \frac{dP_g}{dz} \text{ at } z = 0 \text{ and } z = ZH, \quad (17d)$$

when the platens are opened.

Regarding the air density ρ_a ,

$$\frac{\partial \rho_a u_{xg}}{\partial x} = 0 \text{ at } x = 0 \quad (18a)$$

and

$$\frac{\partial \rho_a u_{yg}}{\partial y} = 0 \text{ at } y = 0 \quad (18b)$$

Regarding the mat temperature T_{mat} , its boundary conditions are more complex:

$$\frac{\partial T_{mat}}{\partial x} = 0 \text{ at } x = 0 \quad (19a)$$

and

$$\frac{\partial T_{mat}}{\partial y} = 0 \text{ at } y = 0 \quad (19b)$$

The edges of the mat are obviously cooler due to heat convection with ambient air. Assume the convection coefficient is h and ambient temperature T_{am} . The mat temperature at the edges are controlled by the following equations:

$$-k_{mat} \frac{\partial T_{mat}}{\partial x} = h(T_{mat} - T_{am}) \text{ at } x = W/2 \quad (19c)$$

and

$$-k_{mat} \frac{\partial T_{mat}}{\partial y} = h(T_{mat} - T_{am}) \text{ at } y = L/2 \quad (19d)$$

When the top and bottom surfaces of the mat are in contact with the platens, a thermal resistance inevitably exists between the platens and mat surfaces. The surface mat temperatures are given by:

$$k_{mat} \frac{\partial T_{mat}}{\partial Z} = \frac{T_{pl,t} - T_{mat}}{R_{tc}} \text{ at } z = ZH \quad (19e)$$

and

$$-k_{mat} \frac{\partial T_{mat}}{\partial Z} = \frac{T_{pl,b} - T_{mat}}{R_{tc}} \text{ at } z = 0 \quad (19f)$$

Here, $T_{pl,t}$ and $T_{pl,b}$ are respectively the temperatures of the top and bottom platens, R_{tc} is the thermal contact resistance [$m^2 \cdot K/W$] between the platens and the mat surfaces.

When the platens are opened, the surfaces of mat are cooled with natural convection with the surrounding air. The cooling surface temperature can be calculated in a similar fashion to the edge cooling.

Material properties

As discussed earlier, the thermal and physical properties of wood composite mats pertaining to hot-pressing are generally not well defined. The data on products such as OSB mats are particularly lacking as the material properties are more dependent upon its structural attributes, i.e., strand size and orientation. Without considering the structural effects, some of the mat properties may be obtained from those of solid wood and from limited published data.

Specific heat.—According to its definition (Kellogg 1981), the heat specific of the mat may be calculated by:

$$C_{mat} = [(1 - \varepsilon)C_s \rho_s + \varepsilon C_g \rho_g] / \rho_{mat} \quad (20)$$

Here, C_g is the specific heat of the gas mixture inside the voids of the mat. The heat capacity of gas inside the mat is much less than that of solid wood. For convenience, C_g is considered as a constant, or $1800 J/(kg \cdot K)$.

For solid wood, the specific heat C_s is affected by both dry wood and water, specifically,

$$C_s = \frac{C_{dry} + C_{water} MC}{1 + MC} \quad (21)$$

Here, C_{dry} and C_{water} are respectively the specific heat of dry wood and water. Assume C_{water} is a constant, or $4190 J/(kg \cdot K)$. The dry wood specific heat C_{dry} is further defined by:

$$C_{dry} = C_{dry,0} (1 + a_T T_{mat}) \quad (22)$$

Here, $C_{dry,0}$ is the specific heat of dry wood at $0^\circ C$ and a_T is the temperature coefficient. Obviously, $C_{dry,0}$ and a_T depend on wood species from which the mat is made, typically, $C_{dry,0} = 1130 J/(kg \cdot K)$ and $a_T = 0.0043/K$.

Latent heat.—There are two types of latent heat, namely, that of free water to steam H_{g1} [J/kg] and bound water to free water H_{g2} . They can be obtained by Humphrey and Bolton (1989):

$$H_{g1} = 2.511 \cdot 10^6 - 2480 \cdot T_{mat} \quad (23a)$$

$$H_{g2} = 1.176 \cdot 10^6 \cdot e^{-MC} \quad (23b)$$

Thermal conductivity.—For convenience, we assume: $k_{mat} = k_{mat,x} = k_{mat,y} = k_{mat,z}$.

The following formula of the mat thermal conductivity k_{mat} [$W/(m^2 \cdot K)$] is obtained from experimental data (von Haas 1998):

$$k_{mat} = a \rho_{mat}^2 + b \rho_{mat} + c \quad (24)$$

Here, ρ_{mat} is the mat density [m^3/kg], and a , b , c are regression coefficients (Table 4)

Permeability.—The following empirical equation was recommended for calculating permeability of OSB mats K_p [m^2] (von Haas 1998):

$$K_p = \exp \left[\frac{1}{a + b \rho_{mat} + \frac{c}{\ln(\rho_{mat})}} \right] \quad (25)$$

TABLE 4. Regression coefficients for thermal conductivity in equation (24) (von Haas 1998).

	MC=0%	MC=6.5%	MC=8.5%
a	-4.15×10^{-8}	-7.02×10^{-8}	-7.37×10^{-8}
b	1.49×10^{-4}	2.04×10^{-4}	2.22×10^{-4}
c	3.02×10^{-2}	2.43×10^{-2}	1.19×10^{-2}

Note: Average strand dimensions: 30.6 mm \times 5.1 mm \times 0.62 mm

TABLE 5. Regression coefficients for mat permeability in equation (25) (von Haas 1998).

	Vertical	Horizontal
a	0.043	0.049
b	-2.79×10^{-6}	-2.41×10^{-6}
c	-0.481	-0.54

Note: Average strand dimensions: 30.6 mm \times 5.1 mm \times 0.62 mm

Here, a , b , c are regression coefficients given in Table 5. The permeability is mainly dependent upon mat density and orientation. Both vertical and horizontal permeability can be calculated using the same equation but their coefficients are different. Note that horizontal permeability in both x and y directions, K_x and K_y are assumed to be the same.

One of the other important variables influencing the mat permeability is wood element size through its effect on inter-element void volume. A model for predicting the void volume and its effect on mat permeability has been developed and will be presented in the second part of this publication series.

SUMMARY AND CONCLUSIONS

A physical-mathematical model for heat and moisture transfer in wood composite mats during hot-pressing is presented. The model mathematically describes the coupled physical phenomenon in composite hot-pressing in terms of mass conservation, momentum of gas flow, energy conservation, thermodynamics, and resin curing kinetics. Presented as a closure mathematical problem, the model consists of fifteen governing equations in order to solve fifteen unknown variables concerning mat environmental conditions including mat temperature, gas pressure, and moisture content. Through the model,

the mat pressing variables are rigorously linked to basic material properties such as mat density, thermal conductivity, and permeability. Initial and boundary conditions for solving the governing equations are also discussed.

The model assumes local temperature equilibrium and isothermal sorptive equilibrium between wood elements and surrounding gas which may need to be modified if wood elements are large. Further studies are recommended to better understand the thermal and isothermal sorptive relationships. More work is also required to characterize the basic mat pressing properties such as thermal conductivity and permeability.

ACKNOWLEDGMENTS

Forintek Canada Corp. would like to thank its industry members, Natural Resources Canada, and the Provinces of British Columbia, Alberta, Saskatchewan, Manitoba, Quebec, Nova Scotia, New Brunswick, and Newfoundland and Labrador for their guidance and financial support for this research.

REFERENCES

- BOLTON, A. J., AND P. E. HUMPHREY. 1988. The hot-pressing of dry-formed wood-based composites. Part I. A review of the literature, identifying the primary physical process and the nature of their interaction. *Holzforshung* 42(6):403–406.
- , ———, AND P. K. KAVVOURAS. 1989a. The hot pressing of dry-formed wood-based composites. Part III Predicted pressure and temperature variation with time, and compared with experimental data for laboratory board. *Holzforshung* 43(4):265–274.
- , ———, AND ———. 1989b. The hot pressing of dry-formed wood-based composites. Part IV. Predicted variation of mattress moisture content with time. *Holzforshung* 43(5):345–349.
- CARVALHO L. A. M., AND C. A. V. COSTA. 1998. Modeling and simulation of the hot-pressing process in the production of medium density fiberboard (MDF). *Chem. Eng. Comm.* 170:1–21.
- DAI, C. 2001. Viscoelastic behaviour of wood composite mats during consolidation. *Wood Fiber Sci.* 33(3): 353–363.
- , AND P. R. STEINER. 1993. Compression behaviour of randomly-formed wood flake mats. *Wood Fiber Sci.* 25(4):349–358.

- , C. YU, AND P. HUBERT. 2000. Modeling vertical density in wood composites during hot pressing. Proc. 5th Pacific Rim Bio-based Composites Symposium, 10–13 Dec. 2000, Canberra, Australia.
- HARLESS, T. E. G., F. G. WAGNER, P. H. SHORT, R. DAN SEALE, P. H. MITCHELL, AND D. S. LADD. 1987. A model to predict the density profile of particleboard. *Wood Fiber Sci.* 19(1):81–92.
- HASELEIN, C. R. 1998. Numerical simulation of pressing wood-fiber composites. Ph.D. Thesis, Oregon State University, Corvallis, OR.
- HATA, T. 1993. Heat flow in particle mat and properties of particleboard under steam-injection pressing. *Wood Research, Bull. Wood Research Inst., Kyoto University.* 80: 1–47.
- , R. KAWAI, EBIHARA, AND H. SASAKI. 1993. Production of particleboard with steam injection. Part V. Effect of particle geometry on temperature behaviors in particle mats and air permeabilities of boards. *Mokuzai Gakkaishi* 39(2):161–168.
- HUMPHREY, P. E., AND A. J. BOLTON. 1989. The hot pressing of dry-formed wood-based composites. Part II A simulation model for heat and moisture transfer, and typical results. *Holzforschung* 43(3):199–206.
- KAUMAN, W. G. 1956. Equilibrium moisture content relations and drying control in superheated steam drying, *Forest Prod. J.* 6(9):328–332.
- KELLOGG, R. M. 1981. Physical properties of wood. Pages 195–218 in F. F. Wangaard *Wood: Its structure and properties*. The Pennsylvania State University, University Park, PA.
- LANG, E. M., AND M. P. WOLCOTT. 1996. A model for viscoelastic consolidation of wood strand mats: Part II. Static stress-strain behavior of the mat. *Wood Fiber Sci.* 28(3):369–379.
- LENTH, C. A., AND F. A. KAMKE. 2001. Equilibrium moisture content of wood in high-temperature pressurized environment. *Wood Fiber Sci.* 33(1):104–118.
- NELSON, R. M. 1983. Jr. A model for sorption of water vapor by cellulosic materials. *Wood Fiber Sci.* 15(1): 104–118.
- SIAU, J. F. 1984. *Transport process in wood*. Springer-Verlag, New York, N.Y.
- SIMPSON, W. T. 1973. Predicting equilibrium moisture content of wood by mathematical models, *Wood Fiber* 5(1): 41–49.
- THOMEN, H. 2000. Modeling the physical processes in natural fiber composites during batch and continuous pressing. Ph.D. Thesis, Oregon State University, Corvallis, OR.
- , AND P. E. HUMPHREY. 2003. Modeling the continuous pressing process for wood-based composites. *Wood Fiber Sci.* 35(3):456–468.
- VON HAAS, G. 1998. Investigations of the hot pressing of wood-composite-mats under special consideration of the compression-behaviour, the permeability, the temperature-conductivity and the sorption-speed (in German). Hamburg, Germany. Pp. 127–146.
- WINISTORFER, P. M., W. W. MOSCHLER, S. WANG, E. DE-PAULA, AND B. L. BLEDSOE. 1999. Fundamentals of vertical density profile formation in wood composites. Part I. In-situ density measurement of the consolidation process. *Wood Fiber Sci.* 32(2):209–219.
- WU, Q. 1999. Application of Nelson's sorption isotherm to wood composites and overlays. *Wood Fiber Sci.* 31(2): 187–191.
- ZOMBORI, G. B., F. A. KAMKE, AND L. T. WATSON. 2003. Simulation of the internal conditions during the hot-pressing process. *Wood Fiber Sci.* 35(1):2–23.