Dynamic Control of Moisture During Hot Pressing of Wood Composites

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Abstract

Hot pressing is an important step in the manufacture of wood composites. In the conventional pressing system, hot press output often acts as a constraint to increased production. Severe drying of the furnish (e.g., particles, flakes, or fibers) required by this process substantially increases the manufacturing cost and creates air-polluting emissions of volatile organic compounds, which are a main source of air pollution from the forest products industry. Wood composites made in the conventional process have high internal stress and low dimensional stability and strength. The development of a pressing technology to improve the process is limited by the release of vapor pressure during hot pressing. A perforated caul system may enlarge the area for the moisture to escape from the board mat during pressing, and thus, make possible high moisture content (MC) pressing. The objectives of this study are to:

1. investigate the MC movement through dynamic control of moisture in hot pressing,
2. determine the thermal conductivity, permeability, specific heat of three major wood composites (medium density fiberboard [MDF], particleboard, and oriented strandboard [OSB]),
3. develop mathematical models for each pressing stage of the conventional pressing process,
4. develop mathematical models for the vacuumed perforated platen pressing process to define temperature, moisture, and vapor pressure gradients in a hot pressing cycle, and
5. evaluate the vacuum effects on the physical and mechanical performance of these wood composites.

A preliminary study on perforated platens showed that the rate of core temperature changes increased with increasing flake MC and number of platen holes. Modulus of rupture (MOR) was highest when the MC was at 8 percent and decreased thereafter as MC increased for all three amounts of platen holes. Internal bond strength increased with the increase of platen hole number per unit area at all MC levels except the 2 percent MC level and decreased with the increase of flake MC levels. This study showed that the perforated caul had the function of releasing moisture and vapor pressure during hot pressing.

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Literature Review

Moisture and transfer during hot pressing

In the manufacture of dry-process wood composites, resin-coated wood furnishes are consolidated into panels between two heated platens. The moisture in a mat is vaporized and transferred in the vertical and horizontal directions from the mat surfaces. Since mat edges are the only areas exposed to the outside environment, vapor pressure is formed in the mat and is responsible for problems such as low core density and internal bond (IB) strength, blows and delamination, and resin wash-in and wash-out effects. To avoid these problems, wood furnishes are dried to a low moisture content (MC). The drying process also results in volatile organic compound (VOC) emissions. The low MC requirement of the conventional pressing system lowers the production of the furnish dryer as well as the entire production line. The rigid requirement on mat MC makes the safety window of the conventional process very narrow and substantial losses are incurred. The solution to this problem requires the use of furnish MC that is higher than what is currently used in commercial plants and an understanding of the mechanism of heat and mass transfer during hot pressing.

The moisture in a mat of a typical dry-process wood composite panel primarily comes from three sources, i.e., the furnish, the resin applied to the furnish, and the condensation reaction after the resin cures. In a typical manufacturing process, mat MC from the furnish may be between 2 percent to 6 percent based on ovendry furnish weight. For structural panels, water-based phenol-formaldehyde (PF) resin is widely used. The solid content of PF resin is about 45 to 50 percent; that is, if 1 percent more of solid resin is added to a mat, more than 1 percent of water is also added to the mat. The typical resin content of a conventional oriented strandboard (OSB) manufacturing process is 3 to 6 percent. That means that about 3 to 6 percent of water is added to the mat along with the resin addition. For the third source, a small amount of extra moisture is added to the board mat by combining two resin molecules and splitting off one water molecule. The total MC of a mat is from 7 to 12 percent, depending on the particular process.

In the process of consolidation, moisture in a mat first changes to vapor under heat and pressure and migrates to the cooler areas of the mat core, edges, and corners along with volatile extractives of the wood furnish and nonreactive adhesive components (Kamke and Casey 1988a, 1988b). The four edges and corners are the only areas from which the moisture can escape during hot pressing. Thus, moisture, temperature, and vapor pressure gradients are formed from face to core and from core to edges (Maloney 1977, Stickler 1959, Suchsland 1962). The mat edges are small compared to the total surface area of the board. Therefore, only a small amount of moisture escapes through the edges and corners; most moisture is released through the panel faces upon opening of the hot press (Maloney 1977). Since excessive moisture may cause blows or delamination, the MC in a conventional process is rigorously controlled in a low range through drying.

MC and its distribution are important factors governing the properties of wood composites. Heat and moisture soften the wood furnish and facilitate plasticization so the wood can be bent without breaking. It is reported that the optimum condition for wood deformation is 15 to 20 percent MC at 100°C (Spelter 1999). The MC of a conventional mat is normally below this range and high swelling would be expected after the panels retake moisture. Rice (1960) found both bending properties and dimensional stability properties are improved by increasing the mat MC from 9 to 15 percent. Moisture may speed the heat transfer from face to core (Kamke and Casey 1988b, Sosnin 1974, Strickler 1959). Drying wood materials is the dominate source of VOC emissions from the wood products industry (Englund and Nussbaum 2000). Englund and Nussbaum (2000) showed that emissions of terpenes and VOC per ovendry weight rapidly increases when the sawdust MC is reduced to below 12 percent (Granstrom 2003). Also, high mat MC may reduce closing time (Maloney 1977), board moisture adsorption and thickness swelling (Maku and Hamada 1955), and internal strain (Kelly 1977, Suchsland 1962). MC adversely influences other properties. Excessive moisture may cause adhesive curing problems, longer pressing time, low core density, and thus low internal bond (IB) strength (Johnson and Kamke 1994, Kelly 1977, Maloney 1977). High MC leads to high gas pressure in the mat (Kamke and Casey 1988b). If moisture is not released sufficiently during pressing, blows or delamination can occur.

There are techniques to reduce or eliminate the negative effects of MC and take advantage of its positive effects. Several endeavors have been implemented to achieve this goal. One technique is to distribute higher moisture in the face than in the core to produce the steam-shock effect (Sosnin 1974, Strickler

1959). Steam-shock is an advance in both pressing theory and technology. Strickler (1959) showed that the heat transfer rate increases with increasing face furnish MC, but modulus of rupture (MOR), modulus of elasticity (MOE), and IB strength decrease when the core MC is at 9 percent.

Steam-injection pressing was designed to reduce pressing time and improve dimensional stability of wood composites. It includes open and closed systems. Both systems use perforated platens to heat the mat through hot steam that is ejected from the holes. In the closed system, the mat is sealed and consolidated under elevated temperature and pressure (Geimer and Kwon 1999, Geimer et al. 1998, Shen 1973). At the end of steaming, pressure is released and the remaining steam is exhausted to the atmosphere. In the open system, mat edges are exposed to the environment, as in the conventional pressing press. Steam is injected from separately heated platens and the mat is consolidated by the heat from the platens and the steam (Geimer and Kwon 1999, Hse et al. 1991, Johnson and Kamke 1994). Composite panels pressed with the steam-injection method have high dimensional stability. This was attributed to the combination of flake plasticization, lignin flow, and chemical modification (Geimer and Kwon 1999). However, high MC in a steam-injected mat results in poor mechanical properties of the mat. This also is the result in the conventional pressing process when the mat has high a MC (Palardy et al. 1989).

The solution to the problem of high moisture pressing is dependent on the release of excessive moisture in the middle of the hot-pressing process. In a typical pressing cycle, the steam pressure is highest in the middle of a mat and diminishes toward the edges, where the steam is released. It is speculated that one or both of the two mat faces may be used as avenues for vapor to escape from the mat during hot pressing to enlarge the moisture-escaping area. One way to implement this is to have holes in the platens so that the evaporated steam may be released through the holes into the atmosphere while the board is being hot pressed.

Modeling on heat and mass transfer

Heat transfer in a medium or between media is due to temperature differences. There are three modes of heat transfer, i.e., conduction, convection, and radiation. If heat transfer occurs across a medium, then the heat is transferred by conduction. Convection heat transfer occurs between a surface and a flowing fluid when they are at different temperatures. Thermal radiation occurs as a surface emitting energy in the form of electromagnetic waves. All of these transfer modes are present during hot pressing of wood composites.

Numerous studies have been conducted on the development of mathematical models of heat and mass transfer in hot pressing. Bolton and Humphrey (1988) conducted a review of the literature on heat and moisture transfer. MacLean (1942) and Carruthers (1959) measured the temperature changes in plywood during hot pressing. Kull calculated heat transfer in flakeboard and built a one-dimensional model (1988) to predict the temperature changes in the mat. Since heat and moisture transfer in composites during hot pressing occurs in three dimensions, one-dimensional models can only predict the moisture and temperature changes in the vertical direction. The one-dimensional model cannot accurately predict moisture and temperature changes in a mat. Bowen (1970) evaluated the convection effects, and Gefahrt (1977) and Kayihan and Johnson (1983) included convection effects in their one-dimensional models.

Humphrey and Bolton (1989) studied the heat and mass transfer in pressing of particleboard. A mathematical model was developed using a finite difference method to predict temperature, MC, and vapor pressure changes in the middle of the particleboard mat during pressing. Both conduction and convection were included in the modeling and circular boards were used to simulate three-dimensional hot-pressing configurations. The initial temperature increase predicted by the model fit well with the experimental results. The developing trend of vapor pressure predicted by the model agrees with the measured values, but the predicted vapor pressure values exceed the experimental ones often by a factor of three. The difference was partially attributed to the long flow paths and the absence of press closure in the model. The model failed to predict the second increase in temperature and was thus valid only for the initial and subsequent vaporization stages.

Kayihan and Johnson (1983) developed a one-dimensional theoretical model for heat and moisture transfer when pressing particleboard. The model was based on three simultaneous systems of equations derived by Luikov (27). Both conduction and convection were included in the model. The model divided a half of the mat thickness into a number of consecutive compartments, each of which was divided into two phases according to the solid to void ratio: void space and wood substance. To include the bulk flow of vapor into the model, a mixing effect was used as a measure to simulate the bulk movement from high- to low-pressure regions. The lateral removal of vapor was treated as "leakage" in the model. The model can be used to predict bound moisture, condensed moisture, vapor pressure, density, vapor moisture, and total pressure profiles at different mat depths. The temperature drops in terms of temperature profiles in the experiments with fiberboard are consistent with the concept of "leaking" introduced into the model.

Dai et al. (2001a, 2001b) developed a finite element model to predict the core temperature, gas pressure, MC, and VDPs of wood and straw composites. Some heat conduction and convection parameters were obtained from experiments and others were taken from the literature. The predicted results of temperature, vapor pressure, and MC agreed well with the experiment.

Harless et al. (1987) developed a one-dimensional numerical model to predict the density profile of particleboard. The model that included heat and mass transfer simulated the physical and mechanical processes that occur in the press and mat system. The closing process was modeled as a series of closing stages, which are distinguished by input values for ram area, power supply, and rate of closure. A mat was described as a series of levels, each of which consisted of two or more mat layers. Mat layers within a level were assumed homogeneous and identical with respect to MC, bulk density, and specific gravity. At the end of any simulated press cycle, the predicted density profile represents layers at different temperatures and moisture values. Empirical data was used to calculate the strain development as a function of temperature and stress without consideration of MC.

The glass transition temperature of a polymer, T_g, is the temperature that corresponds to a change in slope when a specific volume is measured against temperature (1983). The amorphous materials in wood, hemicelluloses and lignin, are glassy regimes when the temperature is below T_g and rubbery when the temperature is above T_g. For hydroscopic polymer materials such as wood, T_g decreases with an increase of MC. The variation of T_g for hemicelluloses and lignin with MC was described by the Kwei Equation (Kelly et al. 1987). Wolcott et al. (1990) used a one-dimensional heat and mass transfer model in conjunction with measured temperature and gas pressure to predict localized MC. The T_g of hemicelluloses and lignin in wood was tracked through the pressing cycle and compared with the measured temperature. The difference between the two temperatures worked as an indicator of flake deformation and stress relaxation, which were used to predict the density profile. The predicted density gradients agreed well with what was measured except when the tracked T_g was below the measured temperature (Wolcott et al. 1990). The accuracy of the techniques is dependent on the sufficient measurement of the difference between the two temperatures. For numerical simulation, errors exist to assume a continuum and local thermodynamic equilibrium, but errors can be minimized by meshing the simulated volume sufficiently small. The huge processing capacity of modern computers can reduce the errors to sufficiently small. The techniques of tracking T_g combined with numerical methods for MC simulation would be more practical and viable for the prediction of temperature, vapor pressure, and moisture levels as well as density gradients.

Of course, the main material in wood composites is wood. Thus, the model used to predict heat and moisture of wood can be adopted and further developed to model the heat and moisture transfer of composites. Kamke and Wolcott (1991) simulated the variation of temperature, vapor pressure, and MC in a pressing mat based on a mathematical model in wood drying. The model first defined the environmental conditions surrounding an individual flake over the entire pressing cycle by estimating the equilibrium moisture content (EMC) using measured local temperature and vapor pressure. Then a one-dimensional model was developed to describe the heat and mass transfer inside of the individual wood flake based on the environmental condition and the wood-drying model. Modeling implicitly assumed that the predicted domain was infinitely large and edge boundaries were neglected. Temperature and EMC of a flake and average flake MC were estimated by the model. The predicted temperature variation agreed with the measurement.

Zombori (2001) developed a two-dimensional model using a finite difference method to predict the variation of temperature, vapor pressure, and MC of single- and three-layer OSB. Modeling was also developed on the basis of a model on wood drying. As in most other models, a substantial discrepancy existed between the predicted and experimental values. The model qualitatively agrees with the experimental data. This was attributed to the material's properties that were obtained from the literature and not the ones on which the model was built. However, two advances were made in this modeling, that is, the inclusion of closing time and heat generated from the exothermic reaction of resin polymerization. A separated probability model was also developed based on flake geometry and density and used to simulate the structural changes of the mat during compression.

Most of the above models began the simulation from the point after press closure. The heat transferred by radiation and time difference of the upper and lower mat surfaces in contacting with the platens were neglected. Closing time is typically more than 10 percent of the total pressing time. From the moment when the mat is put in the press to the moment when the mat is pressed to target thickness, the surface layers of the mat are warmed and temperature and moisture gradients are formed. Errors would result from the selection of boundary conditions in a model without including the press closing. The model developed by Zombori (2001) simulated the entire pressing process including closing time, but the predicted temperature and total pressure were poorly correlated with the experimental measurement in the press-closing period. Another common strategy of most previous modeling was the use of one model to simulate the entire period that was modeled. The extremely complicated interactions among heat and mass transfer parameters, timing, and meshed elements often require a prohibitive computer run time (Zombori 2001). To make the simulation procedure practical, the program either sacrificed the accuracy of the prediction by selecting large meshing sizes or reduced the simulated dimensions or pressing time. The heat transfer mode varies during the pressing period and the mode transitions are needed to be included in the model. But most of the above modeling did not explicitly display the mode transition of heat transfer in the modeling.

Thermal conductivity, permeability, and specific heat depend on material density, MC, and temperature (Hymphrey and Bolton 1989) as well as furnish geometry and species. Humphrey and Bolton (1989) used correction factors in their model to include material density, MC, and temperature effects on thermal conductivity, permeability, and specific heat of particleboard. The parameters used to calculate the correction factors were mostly not measured from the boards on which the model was built. Similar situations exist in most other simulations. The high variability of particleboards and other wood composites makes the parameters, i.e., permeability and thermal conductivity, different from one another. Smith (1980) noted that vapor removal from the board edges is a function of particle geometry. The steam dissipation of flakeboard is slower and the press times are longer than those of particleboard and MDF. Kamke and Casey (1988b) found that a more permeable mat retards the pressure buildup and thus lead to a lower temperature plateau in the core. The difference in furnish shapes also affects the voids in the boards (Lenth and Kamke 1996). Quantitative predictions depend on the accuracy of the material parameters on which the model is built. The way to generalize the model to be viable for other materials is to include the material characteristics in the model.

Current Approach

Modeling conventional pressing

When hot pressing wood composites, the heat to moisture vaporizes water to vapor, but vaporization is limited by the vapor pressure in the mat. After platens contact the mat, heat is transferred mainly by conduction (Bowen 1970, Kamke and Casey 1988b) and moisture in particles on both mat surfaces is vaporized. In a conventional platen system, vapor pressure is formed in thin layers on the top and bottom of a mat at the beginning of a pressing cycle. Thus, when pressing high MC furnish, there is sufficient moisture in these layers and convective heat transfer will play a major role in addition to conduction (Kamke and Casey 1988b). The vaporized moisture would be driven by pressure to the cooler areas in the core, as shown in **Figure 1a** from A to B. There would be no heat transfer in the horizontal direction in this period.

The period from A to B in **Figure 1a** corresponds to A to B in **Figure 1c**, which shows core temperature varies with time in a typical pressing cycle. The incoming water from the face to the core would increase the pressure in the core and condensation is possible (Kamke and Wolcott 1991). The condensation of vapor on particle surfaces gives off latent heat, which increases furnish temperature. The condensed water may sink into particles and increase particle MC. This scenario would prevail throughout the path of the traveling vapor to the mat core until the core temperature reaches the vaporizing temperature. Condensation becomes weaker and vaporization becomes stronger as the temperature rises. The entire process is coupled with the variation in vapor pressure caused by the flake deformation and stress relaxation in the core (Kamke and Casey 1988b, Wolcott et al. 1990). Once the core reaches vaporizing temperature, incoming vapor and evaporated water from the

Figure 1.—*A schematic diagram of moisture flow in a flakeboard mat (a) pressed with a conventional platen system and (b) pressed with a perforated platen system. (c) Core temperature varied with time in a mat of a typical pressing cycle, and (d) vapor pressure in a mat pressed with conventional (solid line) and perforated platen systems (dashed line). H1 to H6 are holes on the upper platen).*

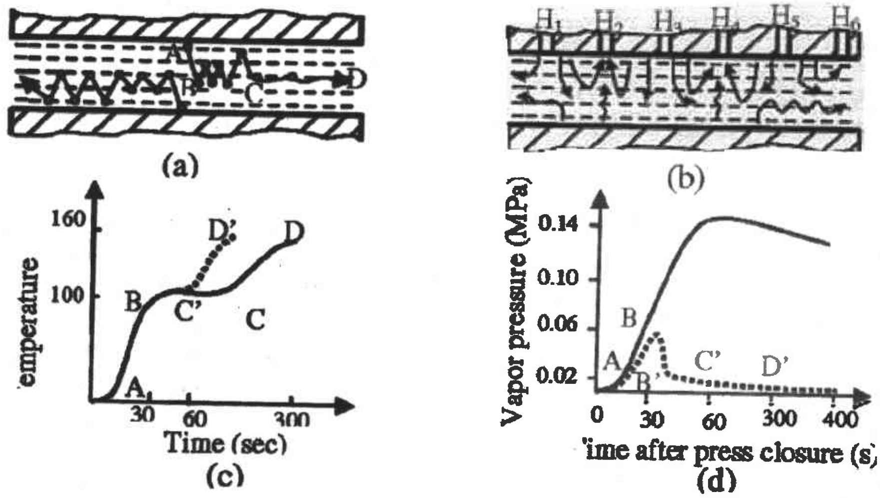

Table 1. *Heat transfer modes in normal and parallel to mat face directions of both traditional and perforated caul systems.*[a]

	Up to stops		A to B[a]		B to C or C'		C to D or C' to D'	
	Normal to face	Parallel to face	Normal to face	Parallel to face	Normal to face	Parallel to face	Normal to face	Parallel to face
Traditional system	CD[b]	--	CD, CV[c]	--	CD	CV	CD	CD, CV
Dynamic system	CD	--	CD, CV	--	CD	--	CD	--

[a] The capital letters refer to Figur
[b] CD - conduction
[c] CV - convection

particles would quickly increase vapor pressure in the core. Further temperature rise is controlled by the vapor pressure (Kamke and Casey 1988b). The pressure difference would drive the moisture laterally to the edge areas. Particle MC might be highest at this transition period and reduced as moisture moves to the edges. The line labeled from B to C in **Figure 1a** corresponds to B to C in **Figure 1c**. In this period, conduction is the mode of heat transfer and convection effects become weakened to near zero in the vertical direction. This is evidenced by the results of Kamke and Casey's study (1988a), which found that the face and core gas pressures are nearly the same 2 minutes after press closing in pressing flake boards with 15 percent mat MC.

As shown in **Table 1**, heat is transferred by different modes at different pressing stages. This requires that simulation should be conducted for each of the stages of a pressing cycle. Models for a cycle can be obtained through the connection of each stage. This approach also reduces the computer processing time by running one stage at a time. The data obtained at the end of one simulation works as the boundary conditions of the next stage run. In this study, the pressing cycle will be simulated in four stages. They are:

I. The period from the moment when the mats are put into the press to the moment when the platens press to designed thickness. Preheating from top and bottom surfaces will be taken into account.

II. The period from the end of Stage I to the moment when the core reaches vaporization temperature (A to B in **Fig. 1c**).

III. The period from the end of Stage II to the moment when no liquid water exists in the core layer (B to C or C' in **Fig. 1c and d**). This is an isothermal stage.

IV. The period from the end of Stage III to the moment when the press is open (C to D or C' to D' in **Fig. 1d**).

In Stage I, heat transfer is mainly by conduction in addition to radiation. In this approach, radiation and heating differences between the upper and lower mat surfaces will be taken into account. Since mat density keeps changing before the platens reach target thickness, the conductivity (k), permeability (K), and specific heat (c) would change with density and temperature. These parameters can be obtained experimentally. Stage I will be further divided into seven stages, and the heat and mass transfer in each of the stage will be modeled (Harless et al. 1987). In Stage II, heat is transferred by both conduction and convection in the vertical direction for both dynamic and conventional processes. There would be no heat transfer in the horizontal direction. In Stage III, heat is transferred by conduction in the vertical direction and by convection and conduction in the horizontal direction. There are moisture gradients in both the vertical and horizontal directions. Vapor pressure gradients exist in the horizontal but not in the vertical directions. In Stage IV, heat is transferred by conduction in the vertical direction and by conduction and convection in the horizontal direction. There are moisture and pressure gradients in the vertical and horizontal directions.

In this study, the Explicit Form of the energy balance method (a finite difference method) will be used to simulate the variation of temperature in a three-dimensional space for each of the four stages (i.e., I to IV). Each stage takes the results of the previous stage as the boundary or initial conditions. The temperature variation lines for a pressing cycle can be obtained by connection of the lines from each of the four stages.

The energy balance method assumes that all heat flow is into the node. The general form of the energy balance equation is expressed as:

$$\dot{E}_{in} + \dot{E}_g = \dot{E}_{st} \qquad [2]$$

where:

$\dot{E}_{in}$ = energy that flows into the node,
$\dot{E}_g$ = energy generated in the node, and
$\dot{E}_{st}$ = energy that is stored.

In three-dimensional space, each node has six neighboring notes (four are shown in Fig. 2). Energy exchange is influenced by conduction and convection between m, n, k, and its six adjoining nodes, as well as by generation. Then Equation [2] may be expressed as:

$$\sum_{i=1}^{6} q_{(i)\to(m,n,k)} + \sum_{i=1}^{6} s_{(i)\to(m,n,k)} + \dot{q}(\Delta x, \Delta y, \Delta z) = \dot{E}_{st} \qquad [3]$$

where:

$q_{(i)\to(m,n,k)}$ = conduction rate between nodes,

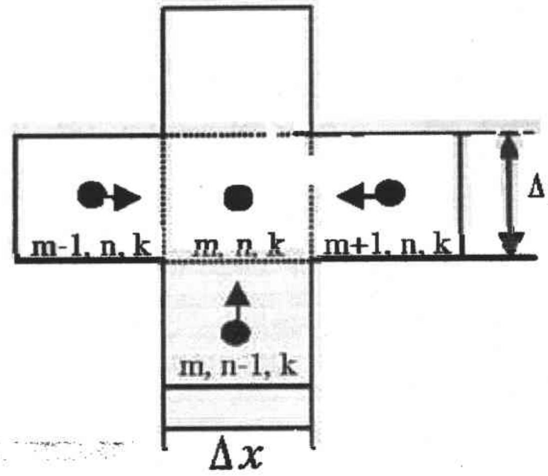

Figure 2. — *Conduction and convection to an interior node from its adjoining nodes.*

$s_{(i)\to(m,n,k)}$ = convection rate between nodes, and
$\dot{q}(\Delta x, \Delta y, \Delta z)$ = heat generation rate.

According to Fourier's law, the rate at which energy is transferred by conduction from node $m-1, n, k$ to m, n, and k may be expressed as:

$$q_{(m-1,n,k)\to(m,n,k)} = \frac{k_x(\Delta y \Delta z)}{\Delta x}(T^p_{m-1,n,k} - T^p_{m,n,k}) \qquad [4]$$

and the convection transfer rate from node $m-1, n, k$ to m, n, and k is the sum of latent heat of vaporization of free water and heat produced when liquid water is adsorbed by an infinite mass of material. It may be expressed as:

$$s = (H_L + H_w)D_v V_v$$

where:

H_L = latent heat of vaporization ($J\ kg^{-1}$),
H_w = adsorption heat ($J\ kg^{-1}$),
D_v = vapor density ($kg\ m^{-3}$), and
V_v = vapor volume (m^3).

According to Darcy's and Fick's laws (Siau 1995), the vapor volume V_v in Equation [5] can be calculated by Equation [6]:

$$V_v = \frac{KAt(P_2^2 - P_1^2)}{2LP_2 n} + \frac{D_m At \rho_w G \Delta M}{100L}$$

where:

K = specific permeability of wood composites (m^2),
A = cross sectional area of flow path (m^2),
t = duration of flow period (sec.),

L = conducting length (m),
P_2 = upstream pressure ($N\ m^{-2}$),
P_1 = downstream pressure ($N\ m^{-2}$),
n = vapor dynamic viscosity ($kg\ m^{-1}s^{-1}$),
D_m = vapor diffusivity ($kg\ m^2s^{-1}$),
ρ_w = normal density of water ($kg\ m^{-3}$),
G = specific gravity of wood (1,000 $kg\ m^{-3}$), and
ΔM = MC difference (%).

The convection transfer rate from node $m-1, n, k$ to m, n, and k can be obtained by substituting Equations [6], Equation [7], and Equation [8] into Equation [5],

$$s = a\ f(H,P,RH,K,t)\frac{\Delta y \Delta z}{\Delta x} \qquad [7]$$

where:

$$f(H,P,RH,K,t) \quad (H_L \quad H_w)P_{sat} \times RH \times$$

$$10^{-8} \times \frac{K\Delta t(P_2^2 - P_1^2)}{2Pn}$$

a = percentage of condensed or evaporated water (%).

The heat generated by the exothermic reaction of glue can be expressed as (Zombori 2001):

$$\dot{E}_g = H_g \rho_g\ \Delta F \qquad [8]$$

where:

H_g = exothermic heat of glue polymerization ($J\ kg^{-1}$),
ρ_g = density of glue ($kg\ m^{-3}$), and
ΔF = reaction index differential.

The energy stored in the node m, n, k may be expressed as:

$$\dot{E}_{st} = \rho c \Delta y \Delta z \Delta \times \frac{T^{p+1}_{m,n,k} - T^{p}_{m,n,k}}{\Delta t} \qquad [9]$$

where:

ρ = localized mass density of the board mat,
c = specific heat ($J\ kg^{-1}K^{-1}$), and
Δt = time increase (sec.).

After the calculation of the convection and conduction transfer rates from the six neighboring nodes, Equation [3] can be used to calculate the temperature of this node. The temperature gradients of each step and each time period can be obtained through solving Equation [3] along with boundary and initial conditions. Since the transfer of heat and moisture is coupled together, the moisture and vapor pressure gradients will be obtained simultaneously in the calculation of temperature gradients.

Modeling the vacuum process

To understand heat and mass transfer in depth, specially designed perforated platens will be used to release the vapor pressure during pressing. The horizontal channels connected to the perforations will be connected to a vacuum. **Figure 1a** shows the moisture movement in a mat pressed with such a platen without a vacuum. To accelerated heat transfer, the vacuum will not be applied before the core temperature reaches 80° to 100°C. When moisture is vaporized, a part of the vapor produced may descend in the mat, as in the conventional process. The remainder finds its way through the holes to the environment, as shown in **Figure 1b**. Thus, "U" shapes of vapor tracks would be expected throughout the mat thickness. Vapor pressure in regions near holes will be lower than that in the conventional process. However, perforations have little effect on heat transfer due to relatively small areas of the holes. After the moisture in the mat core reaches 80°C to 100°C, most wood furnish throughout the path of moisture is plasticized. Keeping moisture in the mat any further would be detrimental to the board. The saturated moisture would retard the further increase of temperature in the core (Kamke and Casey 1988b) and wash out the resin on furnish surfaces. The moisture should be removed as quickly as possible or practical. This is when a vacuum starts. If a vacuum is applied to the holes at point B in **Figures 1c and d**, vapor will be evacuated and vapor pressure will drop, as indicated by the dashed line shown in **Figure 1d**. Also, a negative pressure will allow possible remaining free water to be quickly vaporized and evacuated out of the mat. Parts of the resin that was "washed-in" when the furnish was heated through condensation of water would likely be "washed-out" to the furnish surface as the moisture quickly evaporated. The detrimental effects of "wash-out" can also be reduced or avoided. This would be achieved by finding the optimum time to start the vacuum. The core temperature would increase again with the quick removal of moisture and pressure. The vaporization period, B to C in **Figure 1c**, will be reduced to B to C′ due to the evacuation of moisture by the vacuum. Thus, through dynamically removing the moisture, the pressing time and "wash-out" effects would be reduced. Little heat transfer occurs from B to C′ in the parallel-to-face direction due to the vacuum. The vacuum will be reduced at C′ and stopped when the press starts to release the board. The heat is transferred from C′ to D′ by conduction. As shown in **Figure 1d**, the vapor pressure (the dashed line) after evacuation will be much less than the panel's IB strength, and thus blows or delamination would not occur. **Table 1** summarizes the analysis of heat transfer in a typical pressing cycle.

Four kinds of flow can occur in wood (Siau 1995):

1. viscous or laminar,
2. turbulent,
3. nonlinear, and
4. molecular slip flow or Knudsen diffusion.

The laminar flow occurs when the Reynolds's number is below about 2,000, at which point an external force causes a smooth, streamlined flow with no turbulence. In the simulation of the conventional pressing process, a laminar flow was assumed and Darcy's law was used to describe the mass transfer. When the Reynolds's number exceeds the critical values, laminar flow begins to break down and eddies and disturbances occur. The flow under this condition is turbulent flow. When a vertical vacuum is applied to the mat in the isothermal pressing stage, air and vapor are evacuated from capillary-pore regimes and turbulent flow equations are needed to describe the mass and heat transfer. Under the turbulent conditions, an exponential relationship exists between the flow rate and pressure differentials rather than the linear relationship described by Darcy's law, as shown in Equation [6]. The governing equation for turbulent flow is given below (Kuiko 1966, Siau 1995):

$$Q = \frac{Ak}{\eta}\Delta P\left(1-\frac{S}{\Delta P}\right) \quad \frac{14.79r^{19/7}}{\eta^{1/7}\rho^{3/7}}\left(\frac{\Delta P\bar{P}}{PL}\right)^{\frac{1}{2}} \qquad [10]$$

where:

A = area of pores (m^2),
k = permeability of wood composites (m^2),
ΔP = pressure differentials (Pa),
S = a constant,
η = viscosity of vapor ($kg\ m^{-1}s^{-1}$),
r = diameter of a capillary (m), and
ρ = density of vapor ($kg\ m^{-3}$).

The first term on the right of the Equation is the flow rate in the capillary-porous regions formed between particles, and the second term on the right is the capillary flow rate inside particles.

The perforations in the platens will be separated by an equal distance. In modeling, a grid will be visually superimposed over the board domain. Each hole will be located at the center of one element area in the grid. A finite difference method will be used to simulate the variation of temperature, vapor pressure, and MC in the pressing mat. Since the evacuation is unsteady state mass transfer, the time differential will be small to have an accurate simulation. The turbulent modeling will start from the isothermal stage and will model each element volume to save computer-processing time. The solution of one element will be the boundary and initial conditions of surrounding elements. Heat transfer in the vacuum period is assumed to be conduction.

Results from a Preliminary Study

The experimental variables of this study included three levels of platen hole number (PHN) (no holes is PHN1; low number of holes is PHN2; and high number of holes is PHN3) and five levels of flake MC (2%, 8%, 12%, 17%, and 20%). For each PHN level, the holes were uniformly distributed throughout the aluminum platens, which were 0.32 cm (1/8 in.) in thickness. **Figure 3** illustrates one design of the platens.

Southern pine (*Pinus* sp.) flakes were obtained from a local OSB company in central Louisiana. The flakes were further hammermilled into smaller flakes using a motor miller (Industrial Plus manufactured by Briggs & Stratton Corp., model 133412) at 8 percent MC. The particles were screened on a 6-cm mesh screen, and particles on the screen were then uniformly divided into five groups. Five moisture treatments were randomly applied to the five groups of particles with each group receiving one treatment. The group with a targeted MC of 2 percent was ovendried. The other four groups of particles were conditioned according to the targeted MC of the group in a conditioning chamber. The PF resin used

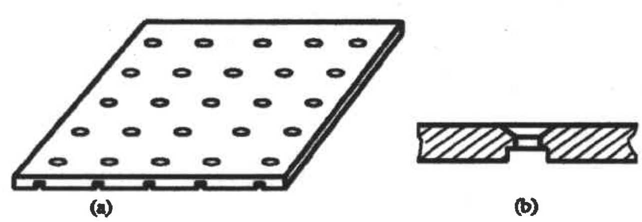

Figure 3. — *Schematic diagram of a perforated caul used in the manufacture of flakeboard: (a) a caul platen and (b) dissection of a particular hole on the caul.*

was obtained from Borden Chemical Company. The solid content of the resin was 51 percent.

Panels were made with a resin content of 4.5 percent. Resin was applied to the particles in a drum blender by an air-atomizing nozzle. The targeted density of the boards was 0.65 g/cm^3. The target thickness of the boards was 12.7 mm. In the middle of the forming operation, thermal couple wires were buried in the geometric center of the randomly formed mats to measure the temperature changes of the mat core during hot pressing. After forming, one of the treatment platens (no holes, low PHN, high PHN) was randomly selected and put on the top of the formed mat as the upper platen. Two boards were made for each combination of MC and PHN variables. For each board, the temperatures of the core were recorded immediately after the pressure reached the maximum and kept recording until the opening of the press.

The boards were tested for MOR, MOE, and internal bond (IB) strength, water absorption (WA), and thickness swelling (TS) according to the ASTM D1037-98.

Temperature changes of the board core with pressing time for the five MCs and three PHN levels are presented in **Figure 4**. Each temperature-time line in **Figure 4** can be divided into three parts. The first part is the linear increase part of the temperature-time lines. The water in the board core began vaporizing at the end of this period, which lasted 1 to 2 minutes after press closure, depending on mat MC. Vaporizing temperatures (VTs) of PHN1 were the highest at the five flake MC levels and all greater than those of other PHN levels. The VTs of boards pressed with PHN3 (i.e., the highest hole density) were the lowest and were almost equal to 100°C for the five moisture levels. Since the vapor pressure is proportional to temperature, the vapor pressure inside the mat for PHN3 level was similar to that of ambient conditions.

One benefit of a high MC is the quick heat transfer from board face to core, or the "steam-shock" effect (29). To analyze the effects of MC on heat transfer from board face to core, linear regression analyses were conducted for the data that represented the linear part of the temperature-time lines in **Figure 4**. The slopes (°C/sec.) of the regression lines are summarized in **Table 2**. As shown in **Table 2**, the holes on the platens slowed the heat transfer from panel face to core at a flake MC below 13.7 percent and had little effect after this MC point. However, the heat transfer rates increased with the increase of mat MC for all

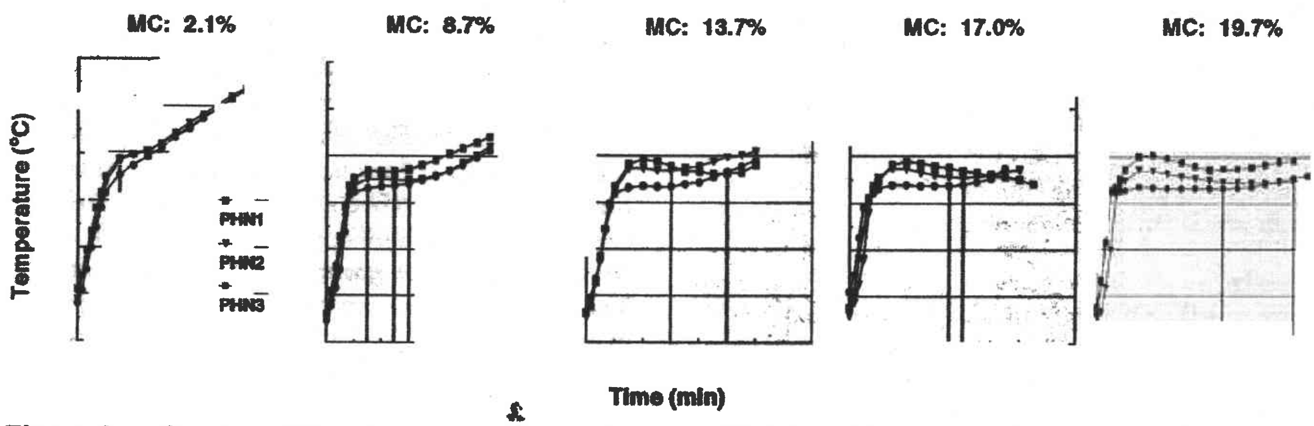

Figure 4. *Core temperature increases with pressing time of flakeboard in a new caul system.*

Table 2.—*Regression slope values (°C/sec of the linear parts in temperature-time lines of boards as affected by number of platen holes (PHN) and MC conditions.*[a]

Targeted MC (%)	2.0	8.0	13.0	17.0	20.0
Actual MC (%)	2.1	8.7	13.7	17.0	19.7
PHN1[ab]	2.08 (0.066)	2.89 (0.105)	2.77 (0.038)	3.27 (0.066)	4.21 (0.430)
PHN2	2.08 (0.032)	2.85 (0.133)	2.48 (0.095)	3.15 (0.501)	4.19 (0.522)
PHN3	2.05 (0.054)	2.66 (0.275)	2.54 (0.142)	3.70 (0.145)	4.53 (0.297)

[a] Values in parentheses represent the standard error.
[b] PHN represents platen hole number: PHN1 – no holes; PHN2 – low hole number (holes/m^2); and PHN3 – high hole number (holes/m^2).

platen number levels. The average temperature rising rates were 3.04°, 2.95°, and 3.10°C per second for PHN1, PHN2, and PHN3, respectively; for different MC levels, the average rates were 2.07°, 2.80°, 2.60°, 3.37°, and 4.31°C per second for 2.1, 8.7, 13.7, 17.0, and 19.7 percent flake MC, respectively.

The second part of the temperature-time lines was from the time when vaporization began to the time when core temperature increased again. Moisture in the mat was vaporized in this period. This period lasted from seconds for 2.1 percent MC to more than 2 minutes for the 17 percent MC for both PHN2 and PHN3. It is noted that the second part never came to an end in the pressing cycle for PHN1 for the flake MC of 17 percent and 19.7 percent. The time used in this period increased with increasing MC and decreased with increasing PHN.

The rest of the temperature-time line is the third part. For the last two flake moisture levels, the third part never came to the PHN1 (17% and 19.7%) because the press was opened before the temperature increased. The highest temperature reached at the end of pressing cycles decreased with increasing flake MCs.

After the boards were pressed, no blow or delamination was found with furnish MC up to 17 percent even though total mat MC was about 22 percent for the fifth group furnish. Although boards pressed with PHN1 did not fail, the bonding between flakes was weak. Boards with 19.7 percent moisture level were delaminated except for one board of PHN3.

Average values and standard deviations of the physical and mechanical properties of tested flakeboard specimens are summarized in **Table 3**. Most boards at 19.7 percent flake MC were delaminated, and the data for these boards was not available. The VDPs of different MC and PHN levels are shown in **Figure 5**.

Moisture had significant effects on flexural properties. **Figure 6** shows that both MOR and MOE reached the highest level when the flake MC was about 9 percent. It is evident that the flexural properties of boards at 2.1 percent flake MC were inferior to those of boards at other MC levels except MOR at the 19.7 percent level. Both MOR and MOE decreased with an increase in MC after the 9 percent flake MC. Both MOR and MOE of PHN3 were lower than the other two PHN levels. However, PHN1 and PHN2 lost more strength than PHN3 as the MC increased from 8.7 to 17.0 percent.

IB values of boards at different PHN and MC levels are shown in **Table 3**. As expected, a high MC deepened the VDP curves for platens without holes; while

Table 3. *Physical and mechanical properties of flakeboard pressed by a new caul system at the five flake MC levels.* [a]

FMC[a] (%)	Platen type[c]	Specific gravity	MOR	MOE	IB	TS[b]	WA[b]	NTS[d]
			------	--- (MPa) ----------			--- (%) ---	
2.1	PHN1	0.66 (0.012)	16.8 (0.73)	2895 (30.5)	0.496 (0.030)	30.78 (2.15)	94.12 (1.67)	14.90 (0.77)
	PHN2	0.67 (0.007)	16.7 (1.33)	2817 (146.0)	0.541 (0.028)	30.29 (1.28)	95.55 (3.33)	14.43 (0.67)
	PHN3	0.65 (0.014)	15.3 (0.99)	2867 (83.8)	0.545 (0.027)	32.43 (2.25)	95.48 (3.92)	13.67 (2.62)
8.7	PHN1	0.63 (0.008)	23.3 (0.52)	3827 (15.9)	0.563 (0.023)	31.49 (1.46)	79.97 (2.20)	17.31 (2.53)
	PHN2	0.68 (0.016)	23.7 (1.63)	3858 (115.6)	0.625 (0.016)	32.00 (3.21)	81.14 (3.38)	14.82 (2.89)
	PHN3	0.65 (0.016)	20.8 (0.81)	3335 (84.6)	0.580 (0.022)	32.14 (1.47)	86.71 (1.88)	16.42 (1.52)
13.7	PHN1	0.67 (0.018)	22.7 (0.45)	3731 (152.2)	0.295 (0.013)	42.10 (2.29)	84.51 (1.08)	26.34 (3.64)
	PHN2	0.69 (0.015)	22.4 (1.72)	3629 (204.0)	0.333 (0.016)	36.65 (1.20)	86.98 (1.61)	21.23 (0.29)
	PHN3	0.68 (0.011)	18.9 (1.21)	3198 (162.9)	0.386 (0.015)	35.69 (2.73)	90.74 (2.34)	19.52 (1.23)
17.0	PHN1	0.65 (0.014)	17.9 (1.81)	3543 (166.6)	0.124 (0.008)	41.21 (4.61)	92.72 (3.54)	24.56 (3.41)
	PHN2	0.67 (0.009)	18.3 (1.15)	3437 (186.4)	0.144 (0.008)	35.59 (2.49)	91.49 (2.72)	18.58 (2.28)
	PHN3	0.67 (0.003)	16.5 (1.21)	3357 (95.2)	0.159 (0.009)	40.36 (2.91)	91.80 (2.18)	22.08 (2.20)
19.7	PHN1	B[e]	B	B	B	B	B	B
	PHN2	0.66 (0.009)	15.1 (0.51)	3602 (62.1)	B	B	B	B
	PHN3	0.68 (0.009)	17.3 (0.46)	3609 (47.0)	0.096 (0.015)	B	B	B

[a] FMC is flake moisture content; NTS is non-recoverable thickness swelling. Values in parentheses represent standard error.
[b] TS and WA were measured after 48-hour soaking.
[c] PHN represents platen hole number: PHN1 – no holes; PHN2 – low hole number (holes/m^2); PHN3 – high hole number (holes/m^2.
[d] NTS was measured after 216-hour soaking.
[e] Some boards in this group blew; property values are unavailable.

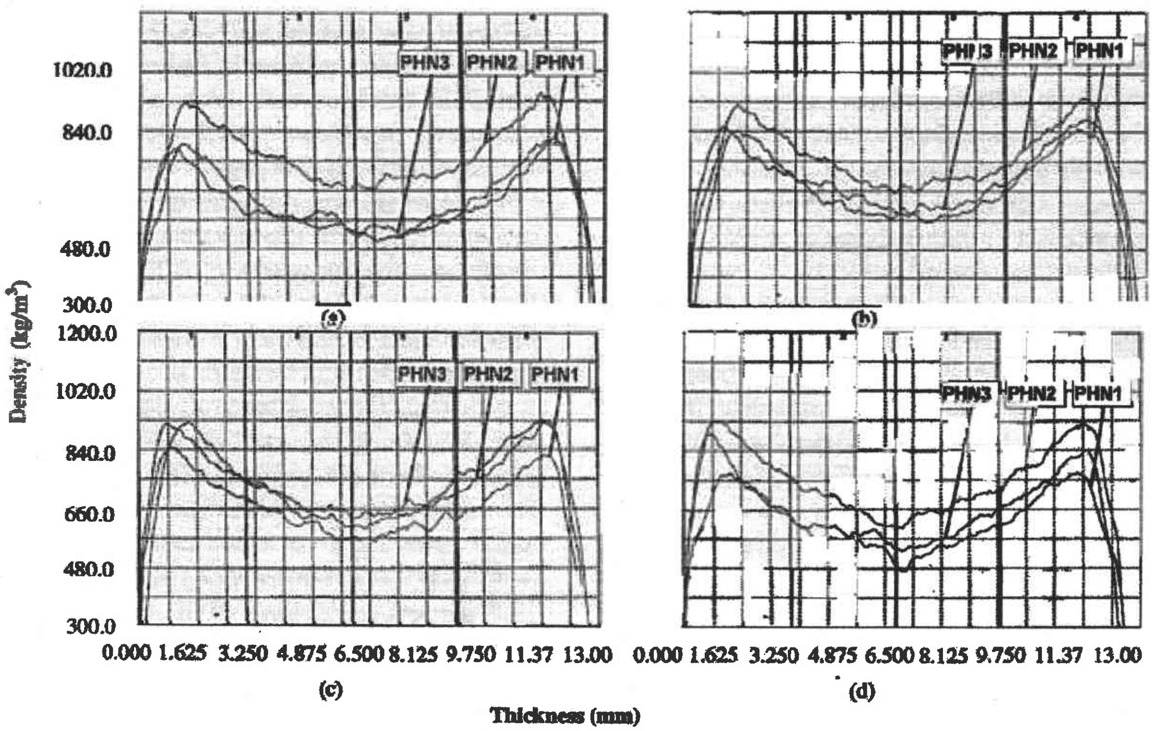

Figure 5. — *VDPs of flakeboard pressed at five levels of flake MC and three platen hole numbers (PHN): (a) 2.1 percent MC; (b) 8.9 percent MC; (c) 13.7 percent MC; and (d) 17.0 percent MC. PHN1 – no holes; PHN2 – less holes; and PHN3 – more holes.*

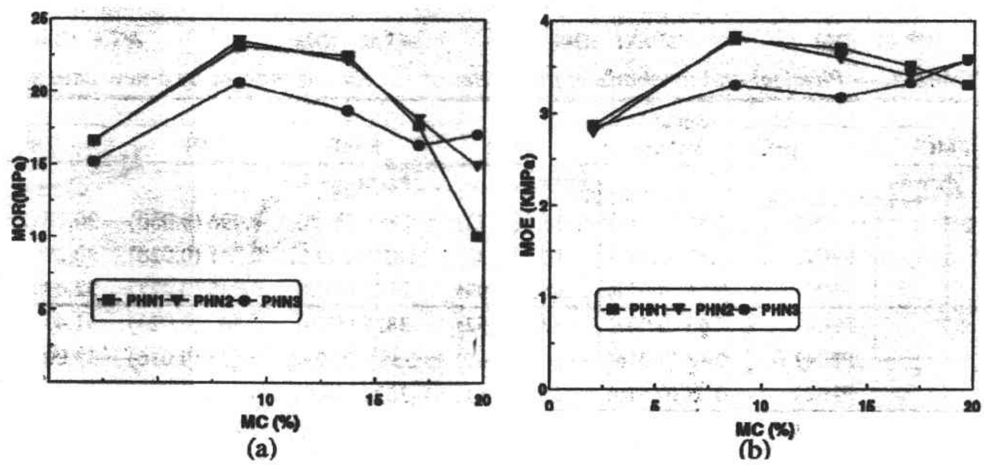

Figure 6. — *Effects of PHN and MC on (a) MOR and (b) MOE of southern pine flakeboard.*

there was little difference in the VDP for PHN3 in the four MC levels. IB strength of the boards increased with the number of holes on the platens. To compare the difference in IB values among three PHNs at each MC level, pairwise comparisons were made and the resulting *p*-values of t-tests are listed in **Table 4**. At 2.1 percent MC level, PHN had no effects on the bonding properties of flakeboard. Since some moisture was released from the board mat once it was vaporized during hot pressing, the "wash-in" and "wash-out" effects were reduced at high MC levels. When the flake MC was 13.7 percent, IB strength increased by 12.9 percent and 30.8 percent as the PHN increased from 1 to 2 and from 1 to 3, respectively. The same percentages of increase were found when the flake MC was 17 percent.

TS and WA after 48-hour soaking and non-recoverable TS after 216-hour soaking are presented

Table 4. — *p-values of two-tail t-tests of IB strength among three platen hole number (PHN) levels of flakeboard pressed at the five MC levels.*

Flake MC (%)	PHN1 to PHN2	PHN1 to PHN3	PHN2 to PHN3
2.1	0.146	0.126	0.915
8.7	0.036[b]	0.593	0.106
13.7	0.094	0.000[b]	0.031[b]
17.0	0.762	0.008[b]	0.061
19.7[a]			

[a] Boards in this group blew; most property values are unavailable.
[b] Values are significant at the 5 percent significant level.

Table 5. — *Regression slope values of relationship between WA and TS as affected by PHN and MC conditions.*[a]

Target MC (%)	2	8	13	17
Actual MC (%)	2.	8.7	13.7	17.0
PHN1[b]	0.16 (0.01)	0.26 (0.04)	0.36 (0.06)	0.36 (0.05)
PHN2	0.13 (0.02)	0.23 (0.06)	0.31 (0.02)	0.28 (0.03)
PHN3	0.17 (0.02)	0.27 (0.04)	0.26 (0.03)	0.33 (0.03)

[a] Values in parentheses are standard error.
[b] PHN represents platen hole number: PHN1 – no holes; PHN2 – low hole number (holes/m^2); PHN3 – high hole number (holes/m^2).

in **Table 3**. Flake MC had significant effects on TS, WA, and non-recoverable TS (NTS). Both TS and NTS increased as MC increased from 8.7 to 13.7 percent. PHN had no effects on TS and WA, but had significant effects on NTS. NTSs were significantly reduced when the boards were pressed with perforated platens (**Table 3**).

The linear relationship between WA and TS was found by Lehmann (1978). A similar relationship between WA and TS was found in this study. The slope values of this linear relationship are presented in **Table 5**. Slope values increased as flake MC increased from 2.1 to 13.7 percent. This indicates that boards pressed at a high flake MC swelled more after soaking unit percentage of water than the boards pressed at a low flake MC. PHN had no effect on the slope values.

Conclusions

The preliminary results show that the perforated caul had the function of releasing moisture and vapor from the mat during hot pressing. In the current platen design, boards can be pressed without blows up to 17 percent flake MC. The perforated caul changed the heat and mass transfer properties of board mat during hot pressing. Flexural and bonding properties of flakeboard were negatively correlated with increasing flake MC when the flake MC was greater than 8.7 percent. IB strength of boards pressed at moderate to high flake MC was significantly improved with increasing PHN levels. Dimensional stability in thickness was negatively correlated with flake MC and improved with increasing PHN levels. Our current and future research include:

1. establish a heat and mass transfer database and finite difference models that quantitatively simulate a pressing cycle of particleboard, OSB, and MDF for both conventional and dynamic pressing systems,
2. ascertain the gas permeability of particleboards, OSB, and MDF as affected by density and MC,
3. determine the thermal conductivity of particleboard and OSB as affected by density, MC, temperature, and furnish sizes, and
4. develop a dynamic pressing system to optimize the properties of wood composites.

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Recent Developments in Wood Composites

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