

Modelling of Vertical Density Profile of MDF in Hot Pressing

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Abstract

The hot pressing operation is one of the most important operations in medium density fibreboard (MDF) manufacture. Complicated dynamic interactions occur during pressing, including heat transfer, moisture movement, development of gas pressure, internal stress development and relaxation, wood consolidation, resin curing, bonding between particles and eventual development of a nonuniform density distribution through the panel thickness. Consequently the mat experiences continuously changing internal conditions (temperature and moisture content) as the pressing operation proceeds.

The vertical density profile (VDP) is one of the most important properties that determine MDF strength and physical properties. The influence of the VDP on the board properties is generally recognised, but the formation of the density profile and their specific effects on the board performance have proved difficult to quantify.

A mathematical model based on theoretical analysis and experimental information is being developed. In the model, the mat is divided into a number of thin parallel layers. The deformation of each layer is a function of stress, temperature and moisture content of the layer. The model considers the variation of the mat mechanical and rheological properties with moisture content and temperature. The changes in temperature and moisture content are provided by a separate heat and mass transfer model. The press model can predict internal pressure, layer deformation and density across the thickness during pressing.

The performance of the model was validated by experiments conducted in a pilot-scale press. Twenty two MDF boards were made with different pressing parameters, and the VDP were measured and compared with the simulation results from the model. The model could predict the density profile with an acceptable accuracy for the main variables that control the manufacturing of MDF boards.

1. INTRODUCTION

The VDP or density distribution through the panel thickness has long been identified as one of the important panel characteristics that correlate well with strength and physical properties of wood based composite panels.

Harless et al. (1987) developed a theoretical model to predict the density profile of particleboard. In their model, heat conduction, gas transport, layer compaction and water phase changes were included in the model. Their simulation terminates when the mat is compressed to the required thickness. Changes in the density profile that might occur after press closure due to differential relaxation were ignored.

Suo and Bowyer (1994) developed a separate model of the particleboard density profile in which the particleboard was considered as a system consisting of a number of thin and uniform layers. The compression properties of these layers were determined as a function of the panel temperature and moisture content. The strain of each layer was calculated during consolidation, and the thickness change of each layer determined the density profile.

A finite-element method was used by Hubert and Dai (1997) in their model for simulation of the hot compression of wood based composites. The model was one-dimensional and only final density profile predictions were reported, with no reference to the time-dependent formation of the profile.

Thomen (2000) developed the most comprehensive model for continuous hot-compression of wood-based composites, which can predict the density profile formation during the entire pressing operation. The viscoelastic properties of the panel were modelled by Thomen using the five element model of Burger-Humphrey. Zombori (2001)

calculated the viscoelastic properties by modified Hooke's law in each time step which determines the stress by multiplying the linear function of strain by a non-linear strain function to represent the nonlinear response of the cellular material to an induced strain.

The present model has overcome some of the limitations of previous models and reduces the computation time significantly. The equation to calculate the modulus of elasticity (MOE) is modified so as to reflect the effect of temperature, moisture content and density of the layer combining the equations of Carvalho et al. (2001) and Palka (1973).

2. CALCULATION OF STRESS-STRAIN

In the press model developed in this work, the MDF board is divided into a number of thin layers, each of which exhibits uniform properties everywhere. Viscoelastic and physical properties of each layer depend upon the stress-strain behaviour of the layer. A denser layer is the result of more deformation or compression having occurred in that layer. The compressibility of a layer is also affected by temperature and moisture content of the layer.

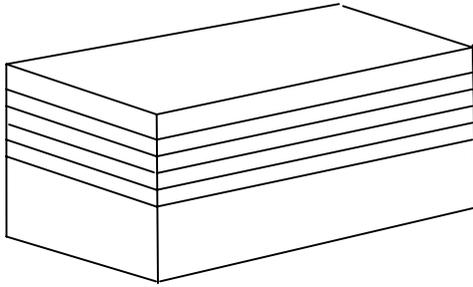


Figure 1. The mat is symmetrically divided into two halves and the upper one divided into a number of layers for simulation

The MDF panel is assumed to be symmetric about the plane of mid-thickness. Thus the equations are solved for only half the panel to speed solution. All layers are assumed to start with the same mass of fibres and the same initial thickness.

The mat behaviour is calculated through a series of time steps during which the board is compressed to the target thickness and then held for a time at that thickness. For each time step, the relative compression in each layer is assumed to be inversely proportional to the MOE of that layer at the start of the time step. This follows the approach

of Suo and Bowyer (1994). They use the term "strain" for ε , but their equations show that they use it to mean the change in thickness. They alter the meaning of ε later in their paper.

The relationship between the strain distributed in different layers and their corresponding MOEs can be described as follows:

$$\varepsilon_{1(\Delta t)} : \varepsilon_{2(\Delta t)} : \dots : \varepsilon_{i(\Delta t)} : \dots : \varepsilon_{n(\Delta t)} \\ = \frac{1}{E_{1(t-1)}} : \frac{1}{E_{2(t-1)}} : \dots : \frac{1}{E_{i(t-1)}} : \dots : \frac{1}{E_{n(t-1)}} \quad (1)$$

By considering the symmetric nature of the panel, the total deformation of the panel in the thickness direction is:

$$2 \sum_{i=1}^n d_{i(\Delta t)} = D_{(\Delta t)} \quad (2)$$

where $d_{i(\Delta t)}$ is the displacement induced in layer i during time interval Δt ($i=1,2,\dots,n$), and $D_{(\Delta t)}$ is the total displacement in the mat in the time interval, corresponding to the movement of the platen. $E_{i(t-1)}$ is the modulus of elasticity of layer i at time $t-1$. The value of 2 in equation (2) is to calculate the strain for the whole board, as n is the number of layers in half the board.

Let

$$S = \sum_{i=1}^n \frac{1}{E_{i(t-1)}} \quad (3)$$

Then the displacement induced in each layer can be calculated as follows

$$d_{1(\Delta t)} = \frac{1}{S} \times \frac{1}{E_{1(t-1)}} \times D_{(\Delta t)} \quad (4)$$

The MOE of individual fibres can be calculated using the equation derived by Carvalho et al. (2001) who derived the equation using data from Wolcott et al. (1990) under various conditions of temperature and moisture content.

$$E_{i(t)} = E_{f_0} \exp\left(-\frac{\beta_T}{T+T_0} + \frac{\beta_H}{H-H_0}\right) \quad (5)$$

In which the parameters: $\beta_T = -1820^\circ C$, $\beta_H = 0.0695$, $T_0 = 447^\circ C$, $E_{f_0} = 6.74 MPa$,

$$H_0 = 0.2925,$$

The effect of density on MOE is quantified by employing Palka's empirical equation (Palka, 1973):

$$E_{i(t)} = E_{i(t-1)} \times \left(\frac{\rho_{i(t)}}{\rho_{i(t-1)}} \right)^p \quad (6)$$

where $E_{i(t)}$ is the modulus of elasticity of layer i at new time t , $\rho_{i(t)}$ is the density of layer i at time t and $\rho_{i(t-1)}$ is the density of layer i at the old time $t-1$. p is the modifications constant for which Palka gives a value of 1.25.

The strain in the mat is calculated by

$$\varepsilon_{(t)} = \frac{M_{(t_0)} - M_{(t)}}{M_{(t_0)}} \quad (7)$$

Where

$\varepsilon_{(t)}$ = mat strain occurring at the time t ,

$M_{(t_0)}$ = initial mat thickness

$M_{(t)}$ = mat thickness at time t .

During the hot-compression, the movement of the hot plate is controlled. Therefore, the total strain of the mat is known. However, the stress relaxation in each layer needs to be determined. In doing so, the time dependent viscoelastic properties are needed. These can be described mathematically by the Maxwell relaxation equation. The governing differential equation of a single Maxwell element given by Zombori (2001) is used to calculate the stress relaxation in different layers.

$$\frac{\partial \sigma}{\partial t} = E \frac{\partial \varepsilon}{\partial t} - \frac{1}{\tau} \sigma \quad (8)$$

After integrating this, the stress change over a short time interval can be calculated by:

$$\Delta \sigma = E \Delta \varepsilon - \frac{1}{\tau} \sigma \Delta t \quad (9)$$

Therefore the iteration formula for a single Maxwell element is

$$\sigma_{i(t)} = \sigma_{i(t-1)} + E_i (\varepsilon_{i(t)} - \varepsilon_{i(t-1)}) - \frac{\Delta t}{\tau_i} \sigma_{i(t-1)} \quad (10)$$

The effects of temperature and the moisture content on the relaxation of the element are taken

into consideration by the method of reduced variables. The relaxation time (τ) is reduced with the temperature and moisture shift factor $a(T, MC)$ as follows:

$$\sigma_{i(t)} = \sigma_{i(t-1)} + E_i (\varepsilon_{i(t)} - \varepsilon_{i(t-1)}) - \frac{\Delta t}{\tau_i a(T, MC)} \sigma_{i(t-1)} \quad (11)$$

The temperature and moisture content shift factor $a(T, MC)$ can be determined by (Wolcott et al., 1990):

$$\log a(T, MC) = \alpha + \beta_1 T + \beta_2 T^2 + \beta_3 MC + \beta_4 MC^2 \quad (12)$$

In which T is the temperature in K and MC is the moisture content in percentage. In Equation (12), the coefficients are given as follows:

$$\begin{aligned} \alpha &= 8.9361, \\ \beta_1 &= 1.027 \times 10^{-1} \\ \beta_2 &= 1.361 \times 10^{-4} \\ \beta_3 &= 1.1908 \\ \beta_4 &= 2.598 \times 10^{-2} \end{aligned}$$

The second term in the iteration formula (Equation 11) is the induced stress due to elastic deformation, and the third term represents the stress relaxation as a function of time, temperature, and moisture content. The temperature and moisture content were calculated at the mesh points. The Maxwell ladder representing the material response was positioned between the mesh points, and therefore, the average of the temperature and moisture contents at the two bounding mesh points were used to calculate the shift factor.

3. RESULTS OF SIMULATION

The program is written in the Matlab software. Due to the complexity of the problem, a modular programming style was chosen. In the simulation, the MDF mat is symmetrically divided into two halves and, once the calculation is complete, graphs of output properties for the complete thickness are generated.

The parameters for a sample calculation are listed in Table 1 and the results plotted in Figures 2-8.

Table 1. Initial parameters for simulation

Panel density	650 kg/m ³
Weight of fibre	1.11 kg
Moisture content	6.78 %
Resin content	9.5 %
Platen temperature	198°C
Pressing time	50 s
Press closing time	15 s
Average thickness	19 mm
Cycle used	Position
Value of p	3.5
Number of layers in half board	10

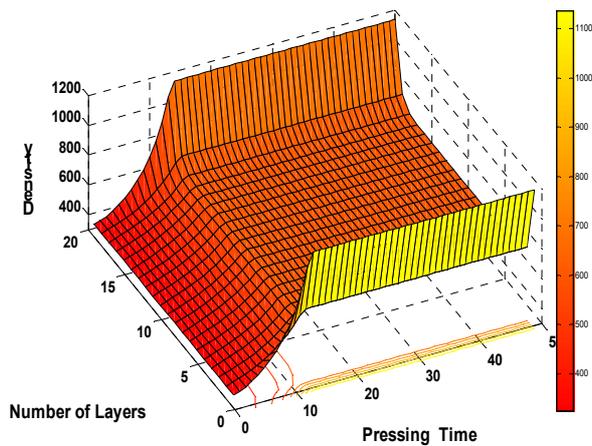


Figure 2. Density of different layers with time

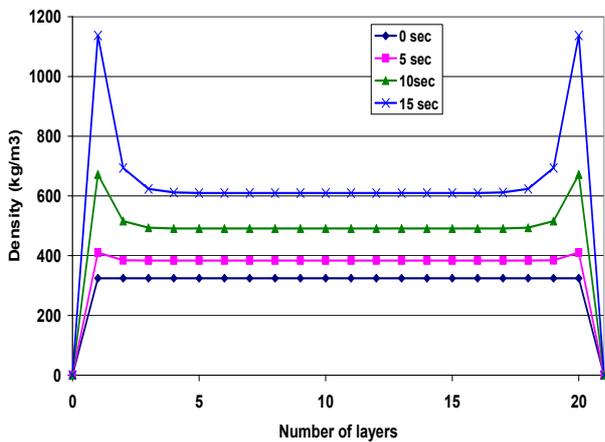


Figure 3. Development of density profile after every 5 second in the 50 sec press cycle

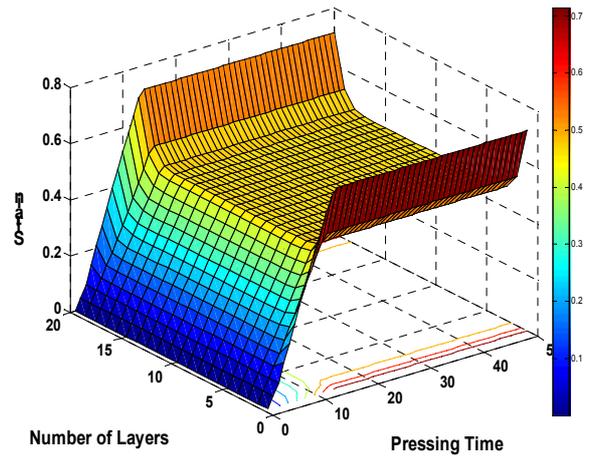


Figure 4. Strain in different layers while pressing

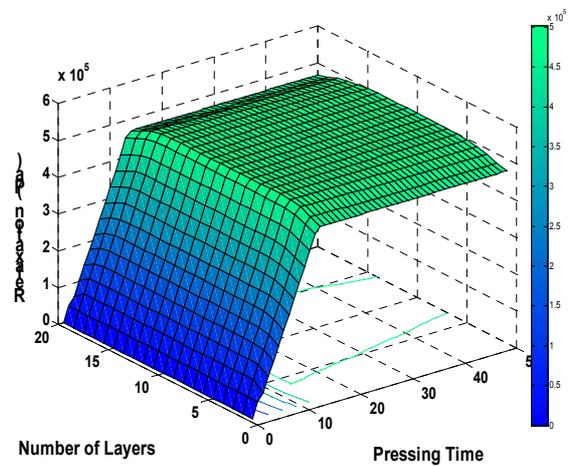


Figure 5. Relaxation stress of fibres across thickness in different layers

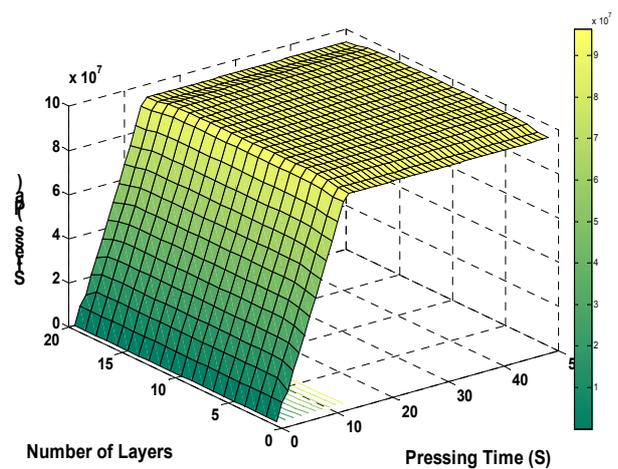


Figure 6. Stress in different layers during pressing

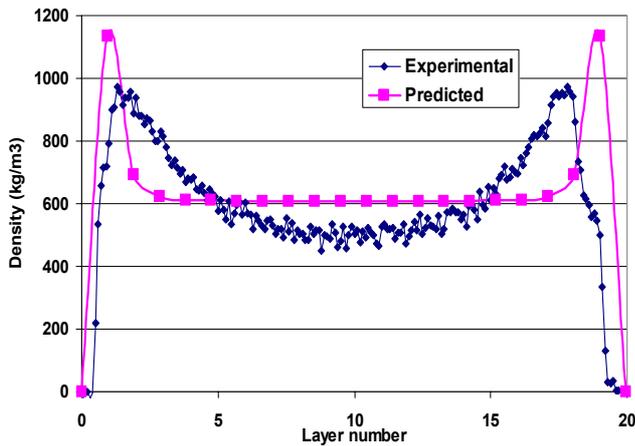


Figure 7. Comparison of predicted and experimental results

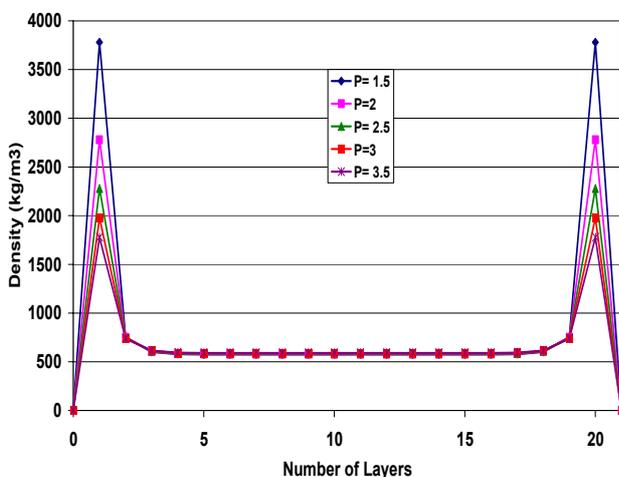


Figure 8. Effect of different values of MOE modification constant "P" on the predicted VDP

4. DISCUSSION

In earlier published models for simulation of VDP in hot pressing of wood based composite panels, the final density profile was taken as that when the press platen reaches its final position. Wang et al. (2000) in their experimental work have shown that small changes in the density profile took place even after final stage, due to spring back and stress relaxation. In this model all these factors were considered.

In Figure 2 and 3, the sequence of development of density profile is shown for every 5 seconds during press closing. The difference between peak and core density increases significantly during pressing.

Figure 4 depicts the amount of strain in different

layers. It is found that there is higher strain in the surface layers than in the core layer. The main reason for this non-uniform strain behaviour is that in the beginning the fibre mat is very loose and could not transfer the platen pressure. The density at the surface increases rapidly in the beginning and after reaching about 600 kg/m^3 then the density in the core starts increasing.

Figure 5 shows the amount of relaxation in different layers. After the platen reaches its final position, the stresses in the fibres start decreasing due to spring back and stress relaxation. In Figure 6, the amount of stress after relaxation in different layers is shown.

In Figure 7 the VDP predicted by the model is compared with the experimental result. The predicted peak and core density is higher than the experimental results. The probable reasons for these differences are first the assumption that surface layer reaches the platen temperature immediately, which increases the plasticity of fibres and cause higher density. Second the mats for experimental boards were formed manually, which may result in nonuniform distribution of fibres. In addition, the MOE was calculated from a modified equation which was initially derived for solid wood, so it gives higher values for initial conditions of fibre mat, when its density ranges from 250 kg/m^3 till 500 kg/m^3 .

In Figure 8, all other conditions were kept constant and the value of the modification constant p was changed. Predicted peak density decreases significantly with increase in it, while there is only slight increase in core density. It is concluded on that basis that for MDF, the value lies some where 3 to 3.5.

5. CONCLUSION

The simulation results give the general trend for the MDF VDP. The peak and core density is higher in comparison to experimental results. The model predicted the general effects of production variables on the density profile formation qualitatively. For quantitative prediction, more reliable data on modulus of elasticity (MOE) and stress relaxation modulus of the fibres needs to be determined experimentally.

6. NOMENCLATURE

d	change in thickness in layer (m)
D	platen movement (m)
E	modulus of elasticity (Pa)
H	mat moisture content (dry basis) (-)
Ho	dimensionless elastic number
M	thickness of mat (m)
MC	moisture content (dry basis) (%)
p	MOE modification constant (-)
S	summation of inverse MOE (Pa^{-1})
t	time (s)
T	temperature (K)

Greek symbols

α	coefficient in equation 12
β	coefficient in equation 12
ε	strain (-)
ρ	density (kg / m^3)
σ	stress (Pa)
τ	time constant (s)

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