Effect of face-layer moisture content and face–core–face ratio of mats on the temperature and vapor pressure behavior during hot-pressing of wood-based panel manufacturing

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Abstract

Wood-based panels are made by consolidating mats of resinous wooden raw materials under a hot-pressing process. This study investigates the effect of face-layer moisture content (MC) and face–core–face (FCF) ratio of mats on the temperature and vapor pressure behavior during the hot-pressing process. Raising the face-layer MC and lowering the face-layer thickness was expected to reduce the time of reaching 100 °C in the hot-pressing process. When the temperature rise was limited or the core temperature decreased after reaching 100 °C (defined as plateau in this study), the mats with 25% and 30% face-layer MC with 1:2:1 FCF ratio reached the highest plateau core temperature, but required a longer time to complete the plateau. The relationship between core plateau temperature and maximum core vapor pressure was well described by the Antoine equation, which empirically models the vapor pressure as a function of temperature. The Antoine equation held across both face-layer MC series (varying face-layer MC at constant FCF ratio) and FCF series (varying FCF ratio at constant face-layer MC). The mat with 20% face-layer MC and 1:2:1 FCF ratio reached 180 °C within the shortest time, regardless of the evaluation conditions.

Keywords: Wood-based panels, Temperature behavior, Vapor pressure behavior, Hot-pressing, Face-layer moisture, Face–core–face ratio

Introduction

Wood-based panels are generally manufactured by consolidating mats of resinated wooden raw materials (for example; strands, particles, or fibers) under a hot-pressing process [1–3]. Hot-pressing is a critical process that not only determines the physical and mechanical properties of wood-based panels [4–7], but also affects the energy consumption and costs on the production line [8–10]. Hot-pressing induces complex and dynamic phenomena viz., heat transfer, mass transfer (mainly moisture vaporization and vapor flow), resin curing, and mat densification within the consolidating mat [1–3, 9, 11]. During hot-pressing, heat is conducted from the heated platen to the mat surfaces [9, 12]. As a result, it vaporizes the surface moisture from the mat. The generated vapor pressure increases with temperature. As the vapor pressure differs between the core and surfaces of the mat, the vapor transfers from the surfaces to the core [9, 12, 13]. By convection, the hot vapor flow causes temperature increments inside the mat. Once the mat temperature has reached the local boiling point of water, the
vaporization is accelerated, and the vapor flows horizontally and escapes from the mat edges. At this time, the rate of the temperature rise stagnates because most of the heat is utilized in the phase change. After a limited temperature rise, the mat temperature gradually increases as heat is conducted from the hot platen because the moisture content (MC) inside the mats decreases [9, 12]. The temperature rise causes thermosetting resin curing and the hydrothermal effect causes mass densification [4, 9, 10, 12, 14]. Therefore, understanding the heat and mass transfer mechanism is important for clarifying the complex physical phenomena inside the mat during hot-pressing.

To understand the heat and mass transfers inside the mat, many researchers have measured the temperature and vapor pressure behavior during hot-pressing. Some studies have reported that the core temperature rises more rapidly in mats with a larger initial MC than in drier mats [8, 12, 15, 16]. Moreover, a high mat MC limits the rise period of the core temperature. The same effect of mat MC was observed in mats with a high aspect ratio or mats formed from dense raw material [12, 17]. Furthermore, when the mat density is high, the rates of core temperature rise and maximum core vapor pressure ($V_{P_{max}}$) increase [8, 15–18], and the core temperature rises more slowly in thicker mats than in thinner mats [8, 16, 17]. Raising the platen temperature and shortening the press closing time has been shown to accelerate the core temperature rise and increase the $V_{P_{max}}$ during hot-pressing [8, 12, 15–17]. Other researchers have developed mathematical models describing the core temperature and vapor pressure behaviors during hot-pressing. For example, Dai et al. [19] developed a simulation model that generally agrees with the measured core temperature and vapor pressure behavior. However, they reported that mat properties such as conductivity and permeability must be experimentally characterized in further study. Hence, investigating the temperature and vapor pressure during hot-pressing by both experimental and simulation approaches is still important.

The effect of mat moisture gradient on the mat temperature and vapor pressure remains under-investigated. As is widely known, spraying water on the mat surfaces (steam shock method) or spraying vapor from the mat surfaces to the core (steam injection method) accelerates the temperature rise in the mat [15, 20]. Steam shock and steam injection improve the convective heat transfer. For the same reason, a high face-layer MC should enhance the heat transfer to the core-layer of the mat. The present study evaluates the thickness effect of face-layers with higher MC than the core-layer. As the heat transfer generally increases through woods with higher MC, we considered that the face–core–face (FCF) ratio under the optimum condition would improve the rate of temperature rise. Therefore, this study aimed to investigate the effect of face-layer MC and FCF ratio of the mat on the temperature and vapor pressure behaviors during hot-pressing. Specifically, it establishes the relationship between each index and the total MC of the mat.

The results of this study are expected to further our understanding of heat and mass transfer during the hot-pressing of mats in wood-based panel manufacture. The ultimate goal is to optimize the performance and production of wood-based panels.

**Materials and methods**

In this study, sugi (*Cryptomeria japonica*) strands were used for making lab-scale wood-based panels (see Fig. 1). The average dimensions of 900 strands are 15 mm length, 2.9 mm width, and 0.18 mm thickness. This element may reduce voids in the mats due to its dimensions and the fact that it is a low-density softwood material. Therefore, we chose this element because we think that it is easy to observe the effect of vapor pressure and temperature on different MC mats. The strands (with an initial MC of approximately 5%) were conditioned by water-spraying, and were placed at room temperature for over seven days inside plastic bags. The target MC of the strands was varied as 10, 12.5, 15, 20, 25, and 30%. The target and measured MCs differed within 1% under all conditions. MC of the mats configures a wide range, which is beyond the current industrial production conditions, because this study aims to understand the temperature and vapor pressure behavior of mats of wide range MC. The mats were hand-formed into three layers (face–core–face) or a single layer. The FCF ratio was defined as the ratio of the dry weight of the strands. Table 1 gives the conditions of the series of experimental mats for evaluating

![Fig. 1 Sugí (*Cryptomeria japonica*) strands used in the experiments](image-url)
the face-layer MC effect. In this series, the FCF ratio was fixed at 1:2:1 and the face-layer MC was adjusted from 10 to 30%. In another series for evaluating the FCF ratio effect, the face-layer MC was fixed at 20%, and the FCF ratio was varied as shown in Table 2. The MC of the mat core-layer was fixed at 10% except for the 1:0:1 FCF ratio mat, which was a single-layer board. The 10% face-layer MC and 10% core-layer MC mats were treated as three layer boards, because they were conditioned in different plastic bags.

The mat was hot-pressed under the pressure of 3 MPa at the press platen temperature of 180 °C. The mat thickness was maintained by a pair of bars separated by 10 mm. The target density, dimensions, and MC of the boards were 0.75 g/cm³, 340 × 320 × 10 mm, and 8%, respectively. Three replicates were produced under each condition. No adhesive was applied, because the aim was to investigate the effect of MC in the mat. Prior to hot-pressing, a temperature and gas pressure sensor (PressMAN Lite, Alberta Research Council, Alberta, Canada), and the temperature and gas pressure were measured at 1-s intervals until the core temperature reached 180 °C. This sensor is a data acquisition system for monitoring internal mat temperature and gas pressure. In this study, since only the mat MC is changed, the main gas pressure is the vapor pressure. Thus, we describe it as vapor pressure, not as gas pressure.

**Results and discussion**

**Effect of face-layer MC on temperature and vapor pressure behavior**

Figure 2 shows the typical core temperature–time and vapor pressure–time curves of the mat series with different face-layer MCs. Under all face-layer MC conditions, the core temperature began increasing at approximately 70 s. Between 70 and 150 s, the mat core rapidly rose to over 100 °C and thereafter remained constant or decreased. Finally, the core temperature increased to the platen temperature. The core-temperature time curves exhibited the same trend as previous studies [8, 12, 21]. The core-temperature behavior was divisible into three stages: an initial stage of rapid temperature rise, an intermediate stage of limited temperature rise or decrease (here defined as the plateau), and a later stage of temperature rise (see Table 3). During the initial stage, the core temperature at the same hot-pressing time increased

![Fig. 2](image)

**Table 1** Series of experimental mats for evaluating the effect of face-layer moisture content (MC)

| Face–core–face ratio* | Target moisture content (%) | Face-layer | Core-layer | Total |
|-----------------------|-----------------------------|------------|------------|-------|
| 1:2:1                 | 10                          | 10         | 10         | 10.0  |
| 1:2:1                 | 12.5                        | 10         | 10         | 11.3  |
| 1:2:1                 | 15                          | 10         | 10         | 12.5  |
| 1:2:1                 | 20                          | 10         | 10         | 15.0  |
| 1:2:1                 | 25                          | 10         | 10         | 17.5  |
| 1:2:1                 | 30                          | 10         | 10         | 20.0  |

* Face–core–face (FCF) ratio was defined as the ratio of the dry weight of the strands contained in the face-layer to the total dry weight of the strands. Underlined mats were also used for evaluating the effect of FCF ratio (see Table 2).

**Table 2** Series of experimental mats for evaluating the effect of face–core–face (FCF) ratio

| Face–core–face ratio* | Target moisture content (%) | Face-layer | Core-layer | Total |
|-----------------------|-----------------------------|------------|------------|-------|
| 1:14:1                | 20                          | 10         | 11.3       |
| 1:6:1                 | 20                          | 10         | 12.5       |
| 1:2:1                 | 20                          | 10         | 15.0       |
| 1:1:1                 | 20                          | 10         | 16.7       |
| 1:0:1                 | 20                          | –          | 20.0       |

* Face–core–face (FCF) ratio was defined as the ratio of the dry weight of the strands contained in the face-layer to the total dry weight of the strands. Underlined mats were also used for evaluating the effect of face-layer MC (see Table 1).
with face-layer MC. In this stage, vaporization of the surface moisture generated a steep vapor flow that accelerated the convective heat transfer to the mat core \[8, 12, 16–18\]. The rise in core temperature with face-layer MC \(\geq 25\%\) at approximately 300 s, and then the core temperature was lower in these mats than in the mats with face-layer MC < 25% at approximately 600 s. In this stage, the heat energy is mainly consumed for the moisture vaporization, because the temperature inside the mat exceeded the moisture boiling point \[16, 18\]. Especially, the core temperature decrement was caused by the high-temperature vapor, which rapidly escaped from the mat core to the mat edge. The vapor escape is thought to accelerate at higher vapor pressures. Indeed, the core vapor pressure was higher in the mats with face-layer MC above 25% than in those with lower face-layer MC (Fig. 2b). Thus, the core temperature in this study appeared to decrease when the \(V_{P,\text{max}}\) exceeded 220 kPa.

### Effect of FCF ratio on temperature and vapor pressure behavior

Figure 3 shows the typical core temperature–time and vapor pressure–time curves of the mat series with different FCF ratios. The core temperature–time curves of the FCF series followed almost the same trends as those of the face-layer MC series, except for the mats with 25 and 30% face-layer MC (Figs. 2a and 3a). After 150 s, 1:0:1 FCF ratio yielded the lowest core temperature at the same hot-pressing time, followed by 1:1:1 FCF ratio and others. The \(V_{P,\text{max}}\) trend of FCF series was same as that of face-layer MC series. However, the \(t_m\) trend of FCF series was different that of face-layer MC series.

### Indices of the temperature–time and vapor pressure–time curves

In the previous subsections, we qualitatively evaluated the core temperatures and vapor pressure behaviors in the mats of the face-layer MC and FCF series. In this subsection, we quantify the relationship between these behaviors and the mat conditions by calculating the time,
temperature, and vapor pressure indices. The indices of the core temperature–time curve were defined as follows: time to reach 100 °C during the initial stage \( t_1 \), plateau temperature \( T_p \) and time to complete plateau \( t_2 \) during the intermediate stage, and time to reach 180 °C \( t_3 \) during the later stage. Table 3 lists the indices computed from the core temperature–time and vapor pressure–time curves, and Fig. 4 shows representative temperature–time curves in the mat core with the indices. In core temperature–time curve without temperature decrease after 100 °C (Fig. 4a), to determine \( T_p \) and \( t_2 \), the tangential lines were set at each time after the temperature reached 100 °C. The slopes of these tangential lines were calculated using the two values at 5 s before and after each time. The core temperature point at which the absolute value of these slopes became the first local minimum was defined as \( T_p \), and the time at which the core temperature was 3% higher than at the last intersection between the tangential line at \( T_p \) and the core temperature curve was defined as \( t_2 \). When the temperature decreased after 100 °C (Fig. 4b), \( T_p \) was defined as described for Fig. 4a, but \( t_2 \) was defined as the time of the minimum core temperature after \( T_p \).

Figure 5 shows representative vapor pressure–time curves in the mat core with the indices. The indices of these curves were \( V P_{\text{max}} \) and the rate of vapor pressure increase \( V P_{\text{rate}} \). Here, \( V P_{\text{rate}} \) defines the rate of vapor generation and vapor flow, and is calculated as:

\[
V P_{\text{rate}} = \frac{V P_{\text{max}}}{t_m - t_s},
\]

where \( t_s \) is the time at which the vapor pressure begins increasing.
Quantitative evaluation of temperature–time and vapor pressure–time curves

This subsection investigates the relationship between the average values of the above-defined indices and the measured total MCs in the series with different face-layer MCs and FCF ratios. In the face-layer MC series, the measured total MCs of the mats with 10, 12.5, 15, 20, 25, and 30% face-layer MC were 10.6, 11.7, 12.2, 15.0, 17.5, and 20.2%, respectively. In the FCF series, the measured total MCs of the mats with 1:14:1, 1:6:1, 1:2:1, 1:1:1, 1:0:1 FCF ratio were 12.1, 13.0, 15.0, 17.1, and 19.3%, respectively. In 19.3% total MC of FCF series, the average value of time indices \(t_1\) was calculated by two samples because the measuring start of one of this series mats was a little delayed. On the other hand, vapor pressure and temperature indices of 19.3% total MC of FCF series were calculated by three samples since we could measure these data correctly.

Figure 6 shows the relationships between \(t_1\) and total MC in the face-layer MC and FCF series. In the face-layer MC series, shorter \(t_1\) resulted in higher total MC. Similar results were reported in previous studies of the temperature behavior in mats with no vertical moisture gradient [8, 12, 15, 16]. The reason for this result might be that the convective heat transfer at mat core increased due to the vapor flow from the mat surfaces. Furthermore, the relationship between \(t_1\) of face-layer MC series and total MC was expressed by a negative linear regression with correlation coefficient \((R = 0.98)\).

In the FCF series, the relationship between \(t_1\) of face-layer MC series and total MC was expressed by a positive linear regression with \(R = 0.97\). This trend clearly differed from those of different MC mats without a moisture gradient [8, 12, 15, 16]. Comparing the trends of the face-layer MC and FCF series, we observed that \(t_1\) was shorter (longer) in the FCF series than in the face-layer MC series at total MCs below (above) 15%. At total MCs below 15%, the FCF series presented higher face-layer MC and lower face-layer thickness than the face-layer MC series (Table 1). Conversely, at total MCs above 15%, the FCF series presented lower face-layer MC and higher face-layer thickness than the face-layer MC series (Table 2). These results suggest that \(t_1\) is shortened in mats with higher face-layer MC and lower face-layer thickness.

Figure 7 plots the relationships between \(VP_{rate}\) and total MC of the mats in the face-layer MC and FCF series. In the face-layer MC series, \(VP_{rate}\) and total MC were strongly positively related \((R = 0.99)\). In mats with higher total MC, the \(VP_{rate}\) increase can be explained by the increased vapor flow from the mat surfaces. This assumption consolidates the relationship between \(t_1\) and total MC in the face-layer MC series (Fig. 6). In the FCF series, the \(VP_{rate}\) increased while the total MC was below 15%, and converged above 15% total MC (the mat with 1:2:1 FCF ratio). Hence, the generation and rate of vapor flow increased up to 50% face-layer thickness, although the face-layer MC of this series was fixed at 20%. Meanwhile, \(t_1\) increased with total MC (Fig. 6). \(t_1\) increased with face-layer thickness even though \(VP_{rate}\) did not rise in the condition above 50% face-layer thickness. This result suggests that \(t_1\) increases even though vapor generation and vapor flow do not rise. Therefore, it is thought that \(t_1\) increases as a result of the heat absorption due to vaporization and the heat transfer of the wood because of the change in the mats FCF ratio. The \(VP_{rate}\) of the face-layer MC and FCF series were almost identical up to 15% total MC, but above 15% total MC, the \(VP_{rate}\) was higher in the FCF series than in the face-layer MC series. This result suggests that the
difference between face-layer MC and FCF ratio did not affect the vapor generation and flow in the mats with total MC \( \leq 15\% \).

Figure 8 shows the relationships between the intermediate-stage plateau period and total MC of the mats in the face-layer MC and FCF series. In the face-layer MC series, \( t_2 \) increased only when the total MC was 17.5\% or lower; otherwise, it was insensitive to total MC. In the FCF series, \( t_2 \) linearly increased with total MC \((R=0.91)\). At total MCs of 15\% or lower, the relationships between \( t_2 \) and total MC exhibited almost the same trends in the two series. Above 15\% total MC, \( t_2 \) was longer in the face-layer MC series than in the FCF series. Note that at total MCs above 17.5\%, the \( t_2 \) indices in the mats of the face-layer MC series cannot be compared because they are defined in different ways. Meanwhile, the \( T_p \) in the face-layer MC series increased up to 17.5\% total MC, and converged at total MCs of 17.5\% and higher (Fig. 8b). As the \( VP_{rate} \) in the face-layer MC series linearly increased with total MC (Fig. 7), it was assumed that convective heat transfer derived from the vapor flow was accelerated at 17.5\% and higher total MCs. Conversely, the high-temperature vapor may rapidly escape from the mat interior, because the core temperatures in the mats of the face-layer MC series reduced when the total MC was 17.5\% or higher (25\% face-layer MC in Fig. 2a). It was assumed that vapor escape did not increase the \( T_p \), but the effect of vapor escape was difficult to evaluate in this study. In future work, the vapor pressure behavior outside the mat core must be investigated along a vertical MC gradient. In the FCF series, \( T_p \) increased at total MCs of 15\% (the mat with 1:2:1 FCF ratio) or lower, and became constant at higher 15\% total MC (Fig. 8b). The \( VP_{rate} \) of the FCF series mats followed a similar trend (Fig. 7). At total MCs up to 15\%, the \( T_p \) trends were almost identical in the face-layer MC and FCF series, but above 15\% total MC, the \( T_p \) was higher in the face-layer MC series than in the FCF series. Despite their higher \( T_p \), mats with total MCs of 17.5\% and higher (the mat with 25\% face-layer MC) in the face-layer MC series required a longer \( t_2 \). A higher \( T_p \) accelerates the resin curing and plasticization of wood in the core-layer, thus increasing the internal bonding in the mat \([5, 14]\). This result suggests that mats fabricated at higher \( T_p \) enhance the mechanical properties of the boards. Thus, it is thought the mats with higher \( T_p \) become the high mechanical properties boards in this study. However, the longer \( t_2 \) indicates a lower productivity at higher \( T_p \). There is also a possibility that \( T_p \) changes due to the adhesive effect when the adhesive is added. To understand how the temperature and vapor pressure behaviors affect the productivity, the mats must be bonded with adhesives and evaluated under different press conditions. The effects of adhesive curing and press condition will be considered in future studies.

When evaluating the relationship between \( T_p \) and vapor pressure, the \( VP_{max} \) was strongly related to \( T_p \) in both the face-layer MC and FCF series (Fig. 9). Rofii et al. \([21]\) reported that the empirical correlation between \( VP_{max} \) and \( T_p \) fits the Antoine equation, which

\[
VP_{max} = a P \times 10^b (\frac{T_p}{100})
\]

where \( P \) is the pressure, \( T_p \) is the temperature, and \( a \) and \( b \) are constants. The Antoine equation was used to fit the empirical data and water vapor, respectively.

![Fig. 8](image1.png) Plateau-period indices \( a \) \( t_2 \) and \( b \) \( T_p \) versus total MC for the mats in the face-layer MC and FCF series. The dashed line in a is the regression line of the FCF series.

![Fig. 9](image2.png) Relationship between \( VP_{max} \) and \( T_p \); the solid and dashed lines are the Antoine correlation fits to the empirical data and water, respectively.
empirically models the vapor pressure \( P \) as a function of temperature \( T \):
\[
P = 10^{(A - \frac{B}{T + C})}.
\] (2)

In this expression, \( A \), \( B \), and \( C \) are constants that must be derived from experimental vapor pressure and temperature. When fitted to the Antoine equation, the relationship between \( V_{P_{\text{max}}} \) and \( T_p \) yielded \( A \), \( B \), and \( C \) values of 5.69, 334.19, and 2.55, respectively. This relationship was highly correlated \((R = 0.96)\). Therefore, it is thought that the relationship between \( V_{P_{\text{max}}} \) and \( T_p \) can be approximated by the Antoine equation, regardless of the difference of face-layer MC and FCF ratio among mats. For pure steam, \( A \), \( B \), and \( C \) are 8.03, 1705.62, and 231.41, respectively [23] (Fig. 9). In this study, a higher core temperature was achieved under lower core vapor pressure than in pure steam. In a previous study [21], the relationship between the intermediate-stage temperature and \( V_{P_{\text{max}}} \) of the mats which have different densities and furnish types followed the Antoine equation of pure steam. On the other hand, in the earlier studies, the vapor pressure in the flake-based different total MC mats was lower than the vapor pressure obtained from the temperature and pressure relationship of pure steam [10]. It is a well-known fact that correlation lines illustrated by the Antoine equation almost overlap that by the temperature and pressure relationship of pure steam. The tendencies of the earlier studies [10, 13] were reflected in the present study. Kamke and Casey [10] posited that the adsorbed water molecules in wood exhibit a lower vapor pressure than pure steam. The mat permeability is also reportedly related to the temperature and vapor pressure behavior [12]. The permeability is thought to change in mats with high face-layer MC because the mat faces densify by the high hydrothermal effect of wooden materials. Moreover, the heat characteristics of wood which are varied by species and densities probably affect the core temperature behavior of the mat. To clarify these effects and better understand the relationship between temperature and vapor pressure inside the mat, we require the continuous accumulation of relevant experimental data.

Figure 10 shows the relationships between \( t_3 \) and total MC in the face-layer MC and FCF ratio mat series. The \( t_3 \) decreased in the mats with total MC contents of 15% or higher (20% face-layer MC with 1:2:1 FCF ratio), and then increased in both series. In mats with lower MC, the temperature is gradually elevated because wood is a poor heat conductor and the convective heat transfer of vapor is a little [8, 12, 15, 16]. Conversely, in mats with extremely high MC, the temperature increase is restrained because a large amount of heat is devoted to water vaporization from the mat. Therefore, an optimum MC condition of the mats is expected. The mat core behavior at \( t_3 \) suggests that the 20% face-layer MC mat with 1:2:1 FCF ratio optimizes the effect of heat transfer which includes the heat conduction from the hot platen, convective heat transfer derived from vapor flow, heat absorption caused by vaporization, and the heat transfer of wood, in this study. When comparing \( t_3 \) of face-layer MC and FCF series, the difference was not observed at 17.5% total MC or lower. On the other hand, at the highest total MC in both series, \( t_3 \) was longer in the FCF series than in the face-layer MC series, even though the \( t_3 \) at the highest total MC of FCF series had a large variation. In the high total MC, it is thought that core moisture requires a longer vaporization time than surface moisture does. In a quadratic regression between \( t_3 \) and total MC, the correlation coefficients of the face-layer MC and FCF series were 0.77 and 0.92, respectively.

The relationship between total MC and \( t_1 \) differed between the FCF ratio and face-layer MC series, but the relationships between total MC and \( V_{P_{\text{rate}}} \), \( T_p \), and \( t_3 \) trended similarly in both series (except when the core temperature decreased over the face-layer MC series). In the absence of a core temperature decrease, these results suggest that the effects of FCF ratio and face-layer MC differ only by the convective heat transfer derived from vapor flow in the initial stage differed. In future work, we must evaluate the effects of the moisture gradient in mats with higher face-layer MC and thinner surfaces than those prepared for this study.

Conclusions
This study evaluated the effects of face-layer MC and FCF ratio on the core temperature and vapor pressure behaviors of mats for wood-based panels during
hot-pressing. Specifically, we quantified the indices of the core temperature–time curves and vapor pressure–time curves of the face-layer MC and FCF series, and investigated the relationship between each index and the total MC. These results suggest that the effect of face-layer MC and FCF ratio only differ by the convective heat transfer derived from vapor flow in the initial stage unless the core temperature decrement does not occur. The main results of this study are summarized below:

1) The index $t_1$ in the initial stage (the rapid temperature-rise stage) decreased at higher face-layer MC and increased at higher FCF ratio. This index is expected to be shortened in mats with higher face-layer MC and lower FCF ratio.

2) The index $T_p$ in the intermediate stage (when the temperature plateaued) was increased in the mats with total MCs of 17.5% or higher (the mat with 25% face-layer MC) in the face-layer MC series, but these mats required a longer $t_2$ than the other mats.

3) The $T_p$ and $VP_{\text{max}}$ were strongly related in both the face-layer MC and FCF series. This relationship was well expressed by the Antoine equation with appropriate constants derived from the data.

4) The index $t_3$ in the later stage (when the temperature rose again) decreased in mats with total MCs of 15% or lower (20% face-layer MC with 1:2:1 FCF ratio), and increased with total MC in both series. The 20% face-layer MC mat with 1:2:1 FCF ratio may have optimized the heat transfer in this study.

The presented results are expected to enhance our understanding of the heat and mass transfers during hot-pressing, and are useful to improve the manufacturing process of wood-based panels.

Abbreviations
MC: Moisture content; FCF: Face–core–face; $t_1$: Time to reach 100 °C in mat core; $t_2$: Time to complete limited temperature rise or decrease (defined as plateau in this study); $t_3$: Time when core temperature reaches the platen temperature; $T_p$: Plateau temperature in the mat core; $VP_{\text{max}}$: Maximum vapor pressure in the mat core; $t_{\text{pr}}$: Time when core vapor pressure starts to increase; $t_{\text{p}}$: Time when core vapor pressure reaches $VP_{\text{max}}$; $VP_{\text{rate}}$: The rate of core vapor pressure increase.

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Authors’ contributions
The first and corresponding author participated sufficiently in the work to take public responsibility for the entire contents of the manuscript. The co-authors participated sufficiently in the work to take public responsibility for part of the contents of the manuscript. All authors read and approved the final manuscript.

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