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CHARACTERISTIC AND PREDICTION MODEL OF VERTICAL DENSITY PROFILE OF FIBERBOARD WITH "PRETREATMENT – HOT PRESSING" UNITED TECHNOLOGY

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ABSTRACT

In order to manufacture fiberboard with different vertical density profile (VDP) and establish predicted model of vertical density profile, the "pretreatment-hot pressing" united technology was used to study the effect of pretreatment parameters on the sandwich layer temperature and the shape factor of VDP. The results showed that the humidification to surface of mats could eliminate the procuring layer and the effect of target density on the shape of VDP could be neglected under united technology. Increasing moisture content, preheating temperature and preheating time could enhance the temperature of sandwich layer after pretreatment process, through which could decrease the surface density deviation and sandwich layer density deviation, increased homogeneity sandwich layer thickness rate and the VDP is converted from "V" shape to "U" shape ,uniform in turn. So the ideal fiberboards with "U" shape (U-FBs) and homogeneity fiberboard (H-FBs) could be produced through regulating and controlling "pretreatment-hot pressing" united technology. The VDP predicted model under united technology built in the study had a very strong predictive ability.

KEYWORDS: United technology, fiberboard, preheating, humidification, vertical density profile.

INTRODUCTION

It is not true that the more uniform or different the vertical density profile (VDP) of fiberboard is, and the better. Fiberboards for different purposes need different VDP shapes. Two kinds of VDPs are much ideal as follows, the one of uniform VDP named homogeneous fiberboard (H-FBs) used for low-density fiberboard cladded with plastic panels. The other kind, with uniform density profiles in sandwich layer and high density variation in surface and sandwich layer, named "U" shape VDP fiberboard (U-FBs), helps to get high strength-weight ratio.

Flat hot-pressing for fiberboard uses thickness gauge to control the mat thickness. Traditional hot-pressing process can be divided into press closure stage, mat thickness adjustment stage and pressure relief stage (Wang 2000, 2001; Winistorfer et al. 2000). Winistorfer et al. (2000) utilized online density monitor system to investigate the VDP variation of fiberboard during the hot-pressing process. It could be concluded that the VDP of fiberboard mainly form from the later period of closure stage and early period of mat thickness maintenance stage, and the later one has limited influence on VDP. The mat compressed process during closure stage and thickness adjustment in early period of thickness maintenance stage is of great significance to the VDP controlment of fiberboard. Wang (2000) adopted stop-closing technology to produce boards of uniform density profiles in sandwich layer.

Pre-curing layer can be eliminated by increasing surface moisture content (Zhang 2009), however high mat moisture content may easily cause defects such as low sandwich layer density, bubbling and delaminating, etc. In this paper, water spraying on the surface was used to get higher moisture content of surface than inner layer before the hot-pressing process, producing "steam impingement" effect which was similar to the effect of hot-pressing by steam infusion, and hence to shorten hot-pressing period, eliminate pre-curing layer thickness and improve product quality (Wang 2000, Zhang 2011, Jin et al. 2009).

In this study, the process of fiberboard manufacture was composed of two sections: Compress process using performing press to press mat to target thickness and adhesive curing process using hot-press with high-temperature. According to target requirement, the VDP could be shaped by mat pretreatment such as surface humidification, mat preheating and surface moisture content adjustment, etc. Like the process of continuous press, the manufacture technology in this paper achieved the goal of traditional hot-pressing process respectively, thickness compression, adhesive curing and moisture content adjustment.

MATERIAL AND METHODS

Raw materials

The fiber, Phenol-formaldehyde liquid resin and emulsified wax used in the studies were from a fiberboard mill located in Beijing which primarily using a mixture of hardwood fiber.

The solid loading levels of resin and wax were 3.5 % and 0.5 % based on the oven-dry weight of the fiberboard respectively. According to the moisture content of each batch of dry fibers, water was added to keep the target moisture content for each mat.

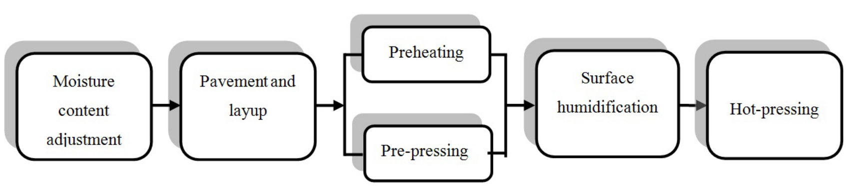


Fig. 1: The process flow of "pretreatment – hot pressing" united technology.

Fig. 1 displays the process flow of "pretreatment– hot pressing" united technology (Short as united technology), of which mat pretreatment process includes moisture content adjustment, mat pavement, mat pre-pressing and preheating with performing press, and pretreatment of both surface of mats.

Mat pretreatment process

1. Parameters selection

The parameters which were comprised of preheating temperature, preheating time, mat moisture content, target density and surface humidification capacity could be shown in Tab. 2. For Urea-formaldehyde resin adhesive generally curing at around 100°C, the preheating temperature was required below 100°C to prevent pre-curing layers.

2. Adjustment of moisture content of fiber

Before gluing, fibers were dried to oven-dry weight. According to the moisture content of each batch of dry fibers. Water was added to keep the target moisture content for each mat. And the glue consumption was 8 %.

3. Pre-pressing and preheating process

All mats were pre-pressed to the target thickness of 12 mm by perform presser with preheating temperature shown in Tab. 1. During the pre-pressing and preheating process, thermocouple was taken to measure temperature variation of sandwich. The targets from U-1 to U-11 shown in Tab. 1 were to produce H-FBs, and enough preheating time was required to make sandwich layer temperature reach preheating temperature, avoiding non-homogeneous VDP caused by temperature gradient.

4. Surface humidification

After pre-pressing and preheating process, humidifying treatment was applied to both surfaces of mats under the conditions shown in Tab. 1.

Hot pressing process

According to the hot pressing curve shown in Tab. 2, pre-treated mats were hot pressed using the thickness gauge of 12 mm. During the hot pressing process, closure time of most mats was shorter than 5 s; hence it could basically be neglected.

Tab. 2: Conditions of hot pressing for fiberboard.

Hot pressing temperature (°C)	Rise time (s)	High-pressure (MPa)	Holding time at high-pressure(s)	Low-pressure (MPa)	Holding time at low-pressure(s)
180	20	3	90	1	230

VDP testing and quantification

The pressed fiberboards were conditioned for 24 hours in a standard conditioning climate of 25°C and 60 % relative humidity before being cut into test specimens. For each board, 50 × 50 mm specimens were prepared for VDP detection without sanding. CreCon's X-ray densitometer was used to measure the VDP of fiberboard specimens. To compare the shape of different VDPs such as differences of surface density and sandwich layer density, fiberboards under united technology could be qualified by three shape factors as follows:

1. Surface density deviation (K_s)

Namely, dividing the difference between the maximum density and the average density by the average density will return a value of density deviation. As the maximum density of top surface and the maximum density of bottom surface were different, the average value of both surface densities could be taken as the maximum density.

$$K_S = \frac{D_{\max} - D_A}{D_A} \tag{1}$$

where: D_{max} - the maximum average density, kg.m^{-3},
K_S - the surface density deviation,
D_A - the average density, kg.m^{-3}.

2. Sandwich layer density deviation (K_c)

Sandwich layer density deviation is the value of the difference between the minimum density of sandwich layer and average density divided by the average density, which can be obtained by the following Eq.:

$$K_C = \frac{D_A - D_{\min}}{D_A} \tag{2}$$

where: D_{min} - the minimum density of sandwich layer, kg.m^{-3},
K_c - the sandwich layer density deviation.

3. Homogeneous sandwich layer thickness rate (KHC)

The thickness rate of homogeneous sandwich layer is the thickness ratio of homogeneous sandwich layer, which could be obtained by the following equation:

$$K_{HC} = \frac{H_C}{H} \tag{3}$$

where: H_C - the thickness of the homogeneous sandwich layer, mm,
K_{HC} - the homogeneous sandwich layer thickness rate,
H - the fiberboard thickness, mm.

In the study, the homogeneous sandwich layer was defined as the area that whose density was lower than 1.05 times of the minimum density of sandwich layer.

SEM analysis of fireboard surface

The specimens were trimmed to smaller than 5×5 mm with surgical knife blade and then sanded by abrasive paper of 400 meshes until no obvious knife mark and burr were founded. They were dried to the oven-dry state at the temperature of 60°C, and sprayed with carbon. Scanning electron microscope produced by HITACHI was used to scan and compare their microstructure.

Tab. 1: Pretreatment parameters and results of united technology.

Panel	Preheating temperature °C	Preheating Time (min)	Mat moisture content (%)	Target density (kg.m^{-3})	Humi-dification throughput (g.m^{-2})	Sandwich layer temperature °C	Surface density deviation	Sandwich layer density deviation	Homogeneous sandwich layer thickness rate
H-1	80	-	8	500	0	80	0.05	0.04	0.86
H-2	80	-	8	600	0	80	0.05	0.07	0.87
H-3	80	-	8	700	0	80	0.07	0.06	0.88
H-4	80	-	8	800	0	80	0.08	0.05	0.79
H-5	80	-	8	700	250	80	0.15	0.08	0.84
H-6	80	-	10	700	250	80	0.18	0.10	0.71
H-7	80	-	10	700	0	80	0.05	0.04	0.87
H-8	80	-	12	700	0	80	0.09	0.07	0.88
H-9	80	-	16	700	0	80	0.06	0.06	0.89
H-10	80	-	8	700	0	80	0.04	0.05	0.92
U-1	20	0	12 %	700	250	20	0.58	0.30	0
U-2	20	5	12 %	700	250	20	0.50	0.24	0
U-3	80	1	12 %	700	250	22.5	0.50	0.24	0.03
U-4	80	2	12 %	700	250	36.7	0.47	0.22	0.07
U-5	80	3	12 %	700	250	44.2	0.44	0.20	0.13
U-6	80	4	12 %	700	250	55.4	0.39	0.18	0.25
U-7	80	5	12 %	700	250	61.5	0.36	0.16	0.37
U-8	80	6	12 %	700	250	66.1	0.33	0.15	0.47
U-9	80	7	12 %	700	250	69.5	0.29	0.13	0.55
U-10	80	8	12 %	700	250	72.1	0.25	0.11	0.67
U-11	80	9	12 %	700	250	74.0	0.21	0.10	0.78
U-12	80	5	8 %	700	250	56.5	0.38	0.18	0.26
U-13	80	5	12 %	700	250	61.5	0.36	0.16	0.37
U-14	80	5	16 %	700	250	65.3	0.34	0.15	0.46
U-15	80	2	12 %	600	250	37.2	0.48	0.21	0.07
U-16	80	2	12 %	700	250	36.7	47	22	6
U-17	80	2	12 %	800	250	36.9	47	21	7
U-18	50	2	12 %	700	250	28.0	48	24	5
U-19	50	5	12 %	700	250	41.1	47	21	7
U-20	50	8	12 %	700	250	46.2	44	19	13

RESULTS AND DISCUSSION

Characteristic of VDP of fiberboards produced by united technology

Fig. 2 displays the VDP of V-FBs, U-FBs and H-FBs. VDP of H-FBs was uniform along the thickness direction, whereas VDP of U-FBs and V-FBs was characterized as the U-shape and V-shape respectively: Firstly, the U-FBs had higher surface density and lower sandwich layer density than those of H-FBs. And the U-FBs had a wider and flatter low-density sandwich layer area; Secondly, there exist continuous density gradient from the surface to the sandwich layer of V-FBs, leading to higher value of surface density deviation and sandwich layer density deviation than U-FBs; Lastly, The pre-curing layer was not found at panel surface of both U-FBs and V-FBs.

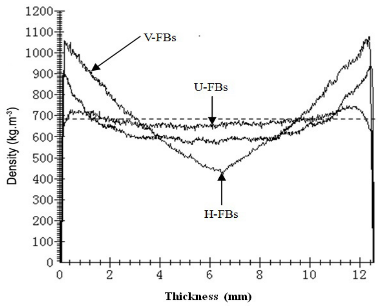


Fig. 2: VDP of fiberboards under united technology. Anotation: The humidification capacity was 250 g.m^{-2}, the average density was 700±20 kg.m^{-3}.

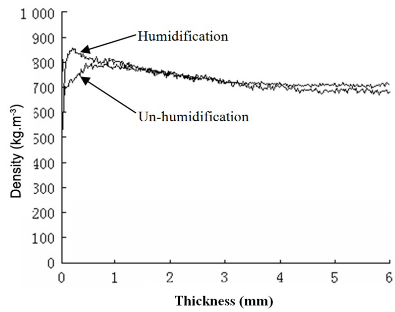


Fig. 3: Effect of surface humidification on the VDP. Annotation: The sandwich layer temperature before hot pressing is 80°C Surface density deviation (Ks), the mat moisture content 8 %, the target density 700 kg.m^{-3}.

H-1 to H-10 in Tab. 1 were of H-FBs, whose surface density deviation was less than 0.2, sandwich layer density deviation was much less than 0.1 and homogeneous sandwich layer thickness rate was above 70 %. Therefore, H-FBs could be conducted by preheating the sandwich layer temperature to 80°C and pre-pressed to target thickness at preheating and pre-pressing process firstly, then be hot-pressed.

U-1 to U-2 in Tab. 1 showed that the surface density deviation was more than 0.5, sandwich layer density deviation was more than 0.24 and no area of uniform density profile existed, which could be considered as the typical V-FBs. The cause of the forming of V-shape was insufficient interior preheating in the united technology.

U-6, U-7 and U-8 in Tab. 1 were typical U-FBs, which showed that the surface density deviation was between 0.3 and 0.4, sandwich layer density deviation was less than 0.2 and homogeneous sandwich layer thickness rate was above 25 %. Proper preheating of the mat in the process of mat pretreatment could produce U-FBs.

It could be concluded that H-FBs and U-FBs could be produced by adjusting the united technology. Compared with the fiberboards produced by the conventional technology, VDPs of fiberboards had some characteristic as follows: Firstly, sandwich layer density increased by adjusting surface density deviation and sandwich layer density deviation properly; Secondly, the pre-curing layers were eliminated and maximum density appeared at panel surface; Lastly, sandwich layer density profile was more homogeneous and sandwich layer density gradient was almost eliminated.

Effect of united technology parameters on the VDP

1. Effect of surface humidification on the VDP under united technology

Namely, dividing the difference between the maximum density and the average density by the average density will return a value of density deviation. As the maximum density of top surface and the maximum density of bottom surface were different, the average value of both surface densities could be taken as the maximum density.

$$K_S = \frac{D_{\max} - D_A}{D_A} \quad (4)$$

where: D_{max} - the maximum average density, kg.m^{-3},
K_S - the surface density deviation,
D_A - the average density, kg.m^{-3},
K_c - sandwich layer density deviation,
K_s - surface density deviation.

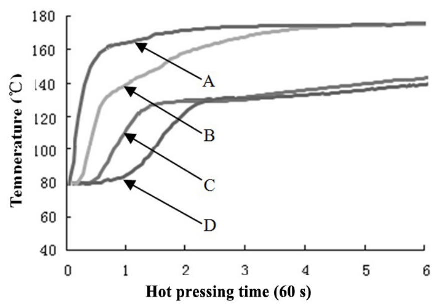
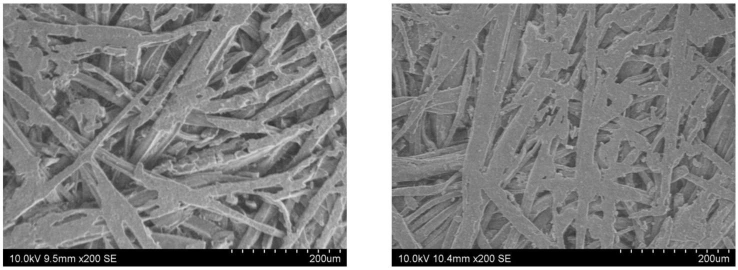


Fig. 4: Effect of surface humidification on the surface temperature and sandwich layer temperature.
Annotation: The preheating temperature was 80°C Sandwich layer density deviation (Kc); the sandwich layer temperature before hot pressing was 80°C; the mat moisture content was 8 %; the target density was 700 kg.m^{-3}.
A: Surface temperature during hot pressing with humidification;
B: Surface temperature during hot pressing without humidification;
C: Sandwich layer temperature during hot pressing with humidification;
D: Sandwich layer temperature during hot pressing without humidification.

Fig. 3 indicates that surface density deviations of the three panels were within 0.2, sandwich layer density deviations were within 0.1, and the homogeneous sandwich layer thickness rate was above 70 %. It could be concluded that fiberboards that pre-pressed sufficiently first and then hot-pressed have a uniform VDP. Compared with un-humidified panels, the surface density deviation of humidified panels increased by 0.05, and the sandwich layer density deviation increased by 0.04 correspondingly.

Fig. 4 displays that humidification treatment could not only greatly shorten the time of sandwich layer reaching curing temperature during the hot-pressing process, but also delayed the rise of surface temperature. When humidification treatment to the mat, the more heat provided by the hot press was used to evaporation of surface moisture and massive surface moisture transferred inwards, which leading to the rise speed of surface temperature slowed down and the mat interior temperature rapidly increased.



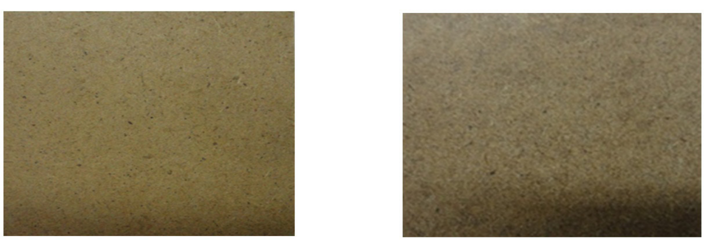
Without humidification | With humidification (humidification capacity of 250 g.m^{-2})

Fig. 5: Effect of surface humidification on fiber arrangement. Annotation: The sandwich layer temperature before hot pressing was 80°C; the mat moisture content was 8 %; the target density was 700 kg.m^{-3}.

The pre-curing layer is the low-density area where the surface fiber touches the hot presser firstly and cured with lower compression ratio at the mat closure stage. Humidified mat surface can reduce the rise speed of surface temperature and increase the compression ratio of surface fiber to eliminate the pre-curing layer and increase surface density. Meanwhile, humidification treatment could accelerate the increase of sandwich layer temperature, which therefore could shorten hot pressing time and enhance production efficiency theoretically.

Fig. 5 indicates the surface characteristic of un-humidified panels: There were lots of pores existed among the fibers, interface of the fibers was little and the fibers were compressed flat. But the humidified surface fiber was compressed totally flat and intimate contacted with little pores between each other. The glue layers among fibers were continuous under humidification because the glue of surface fibers fusing water which cured and formed continuous thin layer in the surface during hot press process. Humidification leaded to reduction of pores among surface fibers and increase of area of continuous glue layers. So, humidified panels had higher surface density and flatter surface than those panels without humidification, and needed less rations of sanding in the following process.

Fig. 6 showed that surface color of un-humidified panels was yellowish, but the humidified panels were darker. Though surface humidification treatment could increase surface density and eliminate the pre-curing layers, it was also required to control the water spraying quantity for it could darken the surface color.



Without humidification | With humidification (humidification capacity of 250 g.m^{-2})

Fig. 6: Effect of humidification on surface color of panel. Annotation: The sandwich layer temperature before hot pressing was 80°C; the mat thickness density was 12 mm; the target density was 700 kg.m^{-3}.

2. Effect of pre-treatment on the VDP under united technology

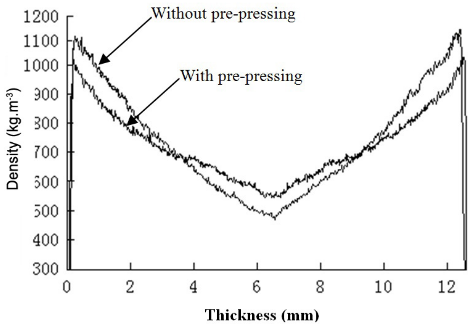


Fig. 7: Effect of pre-pressing on VDP of fiberboard under "pretreatment-hot pressing" united technology. Annotation: The preheating temperature was 20°C; The preheating time was 2 min; the moisture content was 12 %; the humidification capacity was 250 g.m^{-2} the mat moisture content was 12 %; the target density was 700 kg.m^{-3}.

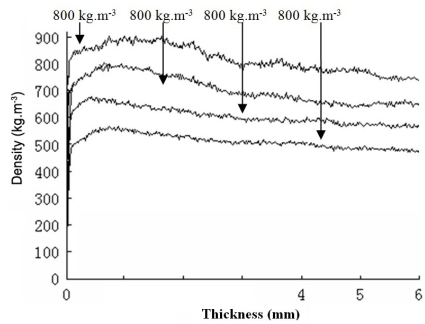


Fig. 8: Effect of different target average density on VDP under united technology. Annotation: The sandwich layer temperature before hot pressing was 80°C; no humidification treatment the mat moisture content was 12 %.

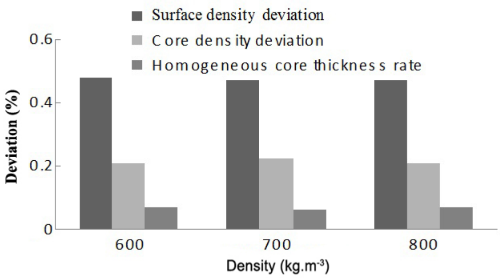
Fig. 7 displays the effect of pre-pressing treatment on VDPs of panels at ordinary temperature. It is shown that sandwich layer density of pre-pressed panels increased by 8.6 % and surface density declined by 5 %. The pre-pressed process could exhaust air in mats and decrease the interior pressure in the hot-pressing process, which rearranged fibers and decrease pores among fibers, increased interface areas between fibers and glues, decreased mat's thickness and obtaining certain density, accelerate the temperature increase of mats and shorten closure time. Therefore the pre-pressed treatment could reduce the closure time in hot-pressed process and the inner stress difference, decreasing the value of surface density deviation and sandwich layer density deviation.

3. Effect of average density on the VDP under united technology

Fig. 8 displays fiberboards of different target density with sandwich layer temperature of 80°C after mat pre-treatment under united technology. It is shown that density profiles within the panels were almost uniform, the value of surface density deviation was between 0.05 and 0.08, and the sandwich layer density deviation was between 0.04 and 0.07, but the value of density deviation of VDP was between 0.09 and 0.13. So the inhomogeneous degree increased a little and the deviation could be neglected. Based on the above analysis, it could be concluded that target average density had little effect on the VDP by hot-pressing and the hot-pressing process has little influence on the VDP when the fiberboards have the same sandwich layer temperature after pre-treatment.

Fig. 9 demonstrates that shape factors of VDP of different target average density varied little under the same united technology. As little effect of the average density on the sandwich layer temperature after pre-treatment, which reached 37°C when preheating at 80°C for 2 min, the moisture content was 12 % and surface water spray quantity was 250 g.m^{-2}.

According to the previous research, target density had little influence on the shape of VDP under united technology.



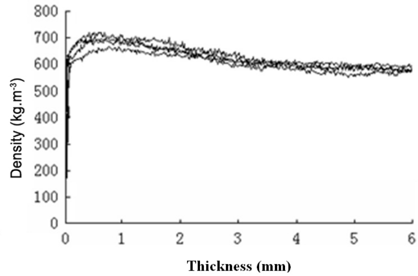
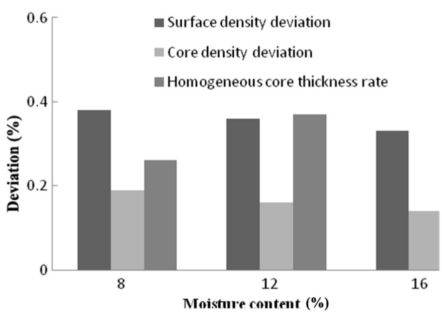


Fig. 9: Effect of different target average density on VDP under united technology. Annotation: The preheating temperature was 80°C; The preheating time was 2 min; the moisture content was 12 %; the humidification capacity was 250 g.m^{-2}.

Fig. 10: Effect of different moisture content on VDP under united technology. Annotation: The sandwich layer temperature before hot pressing was 80°C; the target density was 700 kg.m^{-3}.

4. Effect of moisture content on the VDP in the united technology

Fig. 10 displays the effect of moisture content on VDP produced by united technology with the sandwich layer temperature of 80°C after pretreatment. It is shown that the moisture content has little influence on the VDP when the fiberboards have the same sandwich layer temperature after pretreatment. It resulted from no compressive property difference in the section of mat during hot-pressing process and the negligible effect of moisture on closure time, which verified the comments mentioned above.



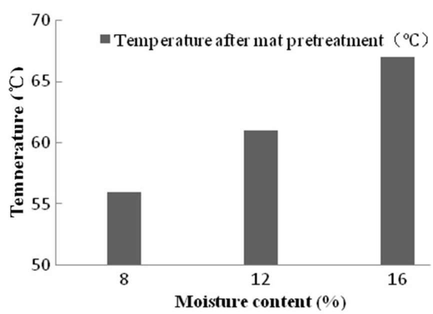


Fig. 11: Effect of different moisture content on VDP under united technology. Annotation: The average density is 700 kg.m^{-3}; the pre hot pressing temperature is 80 °C; the pre hot pressing time is 2 min; the humidification capacity is 250 g.m^{-3}.

Fig. 12: Effect of different moisture content on sandwich layer temperature after mat pretreatment. Annotation: The average density is 700 kg.m^{-3}; the preheating temperature is 80°C; the preheating time is 2 min; the humidification capacity is 250 g.m^{-2}.

Fig. 11 shows that the effect of moisture content on shape factors of VDP under the same united technology. It could be seen that when the moisture content increased, surface density deviation and sandwich layer density deviation both decreased, but homogeneous sandwich layer thickness rate increased. As shown in Fig. 12, higher moisture content lead to higher mat sandwich layer temperature, making VDP after hot-pressing more uniform, which could come to the conclusion that moisture content influenced the VDP under the same united technology, by its effect on sandwich layer temperature during pretreatment in essence.

5. Effect of preheating temperature and time on the VDP in the united technology

As shown in Fig. 13, the effect of preheating time and preheating temperature on factors of VDP could be characterized: longer preheating time lead to less surface density deviation, more sandwich layer density deviation and thicker sandwich layer when preheating time was same. At 80°C, longer preheating time could raise sandwich layer temperature before hot-pressing and decrease the temperature gradient within panels as well as the compressive property deviation along thickness, which could also decrease both the surface and the sandwich layer density deviations, increase sandwich layer thickness and transfer VDP shape from "V" shape and "U" shape to be uniform. Meanwhile at 50°C, different preheating times had effect on shape of VDP slightly, resulting in homogeneous sandwich layer thickness rate below 20 %, and VDP bias towards "U" shape. During the same preheating time, both the preheating temperature and the change amplitude of VDP got higher. Hence, high preheating temperature could change VDP shape effectively.

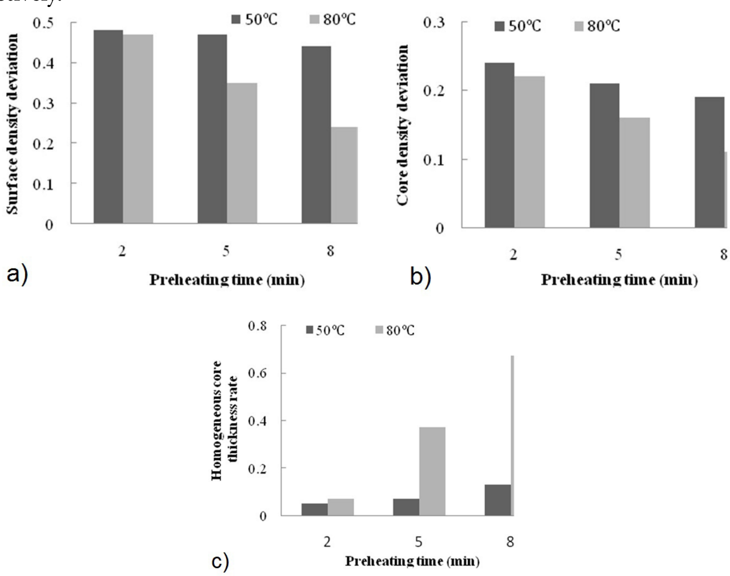


Fig. 13: Effect of different preheating time and temperature on shape factors of VDP under united technology. Annotation: The average density is 700 kg.m^{-3}; the moisture content is 12 %; the humidification capacity is 250 g.m^{-2}.
a) Effect of preheating time on surface density deviation under different preheating temperature;
b) Effect of preheating time on sandwich layer density deviation under different preheating temperature;
c) Effect of preheating time on homogeneous sandwich layer thickness rate under different preheating temperature.

Prediction model of the VDP under the united technology

Based on the analysis mentioned above, shape factors of VDP under united technology could be thought to depend on the sandwich layer temperature after pre-treatment which was related to pre-treatment technology. Therefore, prediction model of VDP in this paper was established by building relation model of "pre-treatment technology –sandwich layer temperature" and "sandwich layer temperature after pre-treatment –shape factors of VDP".

1. Theoretical model of mat temperature model in the pre-pressing process

Hata 1993 proposed a simple way of calculation of temperature within panels in the hot pressing process, and hypothesized the hot-pressing as follows to simplify the analysis:

I. When the platen dimension is much larger than the thickness, heat exchange within the panels can be regarded as a one-dimension unsteady one;

II. Coefficient of temperature conductivity can be seen as a constant;

III. No endogenous pyrogen is found within panels, thus heat produced by the curing reaction of adhesives can be neglected.

The pre-treatment process in this paper has following characteristic such as lower preheating temperature, mat water without phrase transition, larger platen dimension than thickness, thus the preheating process can satisfy the above three conditions. So its heat exchange can be regarded as a unsteady one without endogenous pyrogen. Meanwhile the partial differential equation of Fourier heat exchange can be expressed by:

$$\frac{\partial T}{\partial \tau} = \alpha \frac{\partial^2 T}{\partial x^2} \tag{5}$$

Hata (1993) also considered the hot pressing of panels as a one-dimension and unsteady heat exchange process, and deduced the equation by simplifying boundary conditions as follows (Yu et al. 2004):

$$\begin{cases} \dfrac{\partial T}{\partial \tau} = \alpha \dfrac{\partial^2 T}{\partial x^2} & (0 \le x \le h, \tau > 0) \\ T(x,0) = T_0 & (0 \le x \le h) \\ \dfrac{\partial T(0,\tau)}{\partial \tau} = 0 & \end{cases} \tag{6}$$

where: T -the temperature within panels when heat-pressed,
T_0 - the initial temperature of panels,
α - the coefficient of temperature conductivity along the thickness, $m^2.h^{-1}$,
B - the mat thickness, mm,
x - the distance from a random point to the sandwich layer along the thickness, mm,
τ - the time, s.

Solving the Eq. (6) can obtain the relation between the temperature of any point along the thickness in the preheating process and preheating time:

$$\tau = \frac{36 \times B^2}{10^4 \pi^2 \alpha} \ln \frac{4(T - T_0)}{\pi (T_P - T_0)(\cos \frac{2\pi x}{B})} \tag{7}$$

Eq. (7) is regarded as the classical theory in the study of board hot-pressing and heat exchange. Yu et al. (2004) adopted thermoelectric pair to measure internal temperature and compared that with the obtained results, finding that the deviation between the two was large and the whole hot pressing curve didn't rise successively with a steady temperature process intermediately. This process occurred at about 100°C, which was the process of phase change of water by absorbing heat. Therefore, Eq. (7) only can explain that the temperature-rise period before phase change of water which was a part of the hot-pressing process. However, under the pre-pressing and preheating process in this paper, with the preheating temperature below 80°C, phase change of water within panels will not exist in any position. So Eq. (7) was suitable for pre-pressing and preheating process.

In the pre-pressing and preheating process, coefficient of temperature conductivity of panels is related to the initial temperature and moisture content, and unrelated to the panel density. The equation can be expressed by the following (Xie 2003):

$$\alpha = 10^{-4} \times (a + bT_0 + \ln W) \tag{8}$$

Combining Eq. (7) and Eq. (8), model of temperature variation of any location along the thickness could be concluded as follows:

$$\tau = \frac{36 \times B^2}{(a + bT_0 + \ln W)\pi^2} \ln \frac{4(T_P - T_0)}{\pi(T_P - T)(\cos \frac{2\pi x}{B})} \tag{9}$$

where: a, b - constant relevant to the materials.

It could be concluded from Eq. (9) that temperature variation of any location was related to the mat thickness, preheating temperature, initial temperature and mat moisture content, and independent of panel density.

2. Comparison of measured value and predicted value of sandwich layer temperature variation

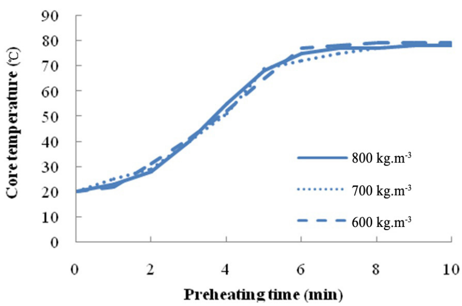


Fig. 14: Effect of panel density on sandwich layer temperature in the pre-pressing and preheating process. Annotation: The moisture content is 16 %; the panel density is 700 kg.m^{-3}.

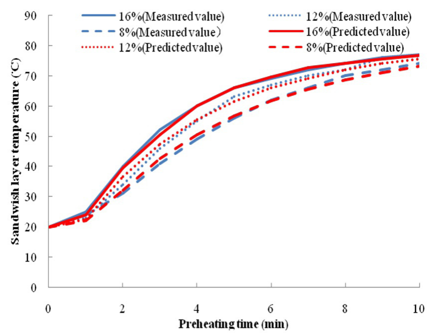


Fig. 15: Comparison of predict value and measured value of sandwich layer temperature of different moisture content. Annotation: The preheating temperature is 80°C; the humidification capacity is 250 g.m^{-2}; the panel density is 700 kg.m^{-3}.

Fig. 14 indicates that panel average density from 600 to 800 kg.m^{-3} had little effect on the heat exchange, which could be neglected. The compressed mat exchange heat by heat conducting of fibers, for little effect of convective heat-transfer caused by low void ratio. Therefore, heat exchange within panels is unrelated to the density in the preheating process.

As the initial temperature T_0 was 20°C, it could be assumed that: $a+bT_0=Z$, Z is a constant. Eq. (9) can be expressed as follows:

$$\tau = \frac{36 \times B^2}{\pi^2 \left(Z + \ln W\right)} \ln \frac{4(T_P - T_0)}{\pi(T_P - T)(\cos \frac{2\pi x}{B})} \tag{11}$$

When $x=0$, the relationship between sandwich layer temperature and preheating time can be expressed as Eq. (11):

$$\left(Z + \ln W\right) = \frac{36 \times 144}{320\pi^2} \ln \frac{24}{\pi} \tag{12}$$

It could be seen from to Tab. 1, with moisture content of 16 %, preheating temperature of 80°C, fiber initial temperature of 20°C, preheating time of 2 min, the sandwich layer temperature was 40°C. Substituting these into Eq. (12), then: Z=0.57. Therefore, under the experimental conditions in this paper, the relationship model of sandwich layer temperature after pre-treatment and preheating time can be expressed as follows:

$$\tau = \frac{36 \times B^2}{\pi^2 \left(0.57 + \ln W\right)} \ln \frac{4(T_P - 20)}{\pi(T_P - T)} \tag{13}$$

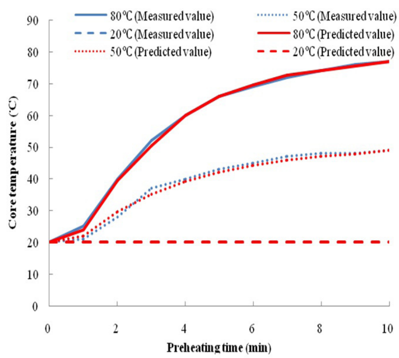


Fig. 16: Comparison of predict value and measured value of sandwich layer temperature with different preheating temperature. Annotation: The moisture content is 16 %; the humidification capacity is 250 g.m⁻²; the panel density is 700 kg.m⁻³.

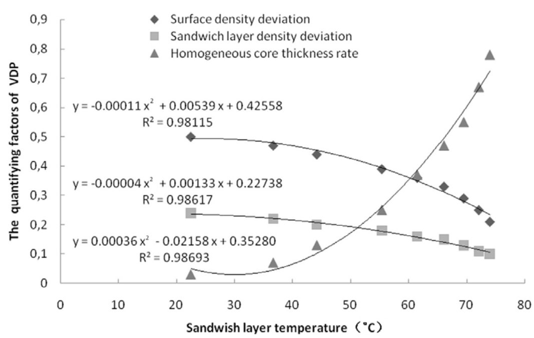


Fig. 17: Relationship between sandwich layer temperature after pre-treatment and the shape factors of VDP. Annotation: The preheating temperature is 80°C; the moisture content is 12 %.

It can be seen from Fig. 15 that under conditions of the same preheating temperature and panel density, panels of higher moisture content have better thermal conductance and a more rapid rising rate of sandwich layer temperature, for capacity of heat transmission of water was much better than dry fibers.

It can be seen from Fig. 16 that under the same conditions of density and moisture content, higher the preheating temperature was, more rapidly the temperature-rise rate became, which could be concluded that high preheating temperature can shorten preheating time greatly. However, for no adhesive curing in pre-pressing and preheating process, the preheating temperature was just below 100°C theory. But in practice, the preheating temperature of 90°C could lead to solidification and delamination easily. When preheating temperature was too low, it could improve temperature within mats hardly and increase preheating time. Therefore, preheating temperature adopted in this paper was below 80°C.

Fig. 15 and Fig. 16 display comparison result of predict value and measured value of sandwich layer temperature under conditions of the different preheating temperature and panel moisture content. It could be seen that predict value of simulation model agreed well to measured value, therefore relationship model of sandwich layer temperature and pretreatment parameters suitable for pre-pressing and preheating process.

Based on the above, it can be concluded that pre-pressing process can increase temperature within mats, meanwhile preheating temperature, panel moisture content and preheating time were the three main influencing factors of sandwich layer temperature during the pre-pressing and preheating process, and panel average density had little effect on the sandwich layer temperature.

3. Effect of sandwich layer temperature after pre-treatment on the shape factors of VDP

According the above analysis, parameters of pretreatment technology influence the shape of VDP by increasing temperature within mats before hot-pressing process.

Therefore, with the preheating temperature of 80°C and moisture content of 12 %, relationship between sandwich layer temperature and shape factors of VDP (Surface density deviation, sandwich layer density deviation and homogeneous sandwich layer thickness rate) can be expressed as the Fig. 17 and R^2 of the relationship between shape factors of VDP and sandwich layer temperature after pre-treatment was above 0.9, which indicated that the equation could be shown as:

$$K_S = -1.1\times10^{-4}T^2 + 5.39\times10^{-3}T + 0.42558 \tag{14}$$

$$K_C = -0.4\times10^{-4}T^2 + 1.33\times10^{-3}T + 0.22738 \tag{15}$$

$$K_{HC} = 3.6\times10^{-4}T^2 - 0.02158T + 0.35280 \tag{16}$$

where: T - the sandwich layer temperature after pre-treatment, °C.

It could be seen from Eq. (14) to Eq. (16) that the relationship between shape factors of VDP and sandwich layer temperature after pre-treatment can be described as quadratic function. Furthermore, sandwich layer density deviation and surface density deviation showed decreasing function relationship with sandwich layer temperature, and homogeneous sandwich layer thickness rate showed increasing function relationship with sandwich layer temperature.

4. Comparison of measured value and predict value from predict model of VDP

Based on research above, it could be concluded that the average density had little effect on the shape of VDP, and moisture content affected sandwich layer temperature in the pre-treatment, but its effect on the hot-pressing process was negligible. Therefore, Eq. (14) to (16) could be assumed as the relationship model between sandwich layer temperature after pre-treatment and shape factors of VDP, the relationship model between parameters of pre-pressing technology and shape factors of VDP could be obtained from Eq. (13) to Eq. (16).

Tab. 3: Comparison of predict value of predict model of VDP shape factors and measured value.

Panel	Surface density deviation K_{ST}	Sandwich layer density deviation K_{CT}	Homogeneous sandwich layer thickness rate K_{HT}	Predicted value of surface density deviation K_{SP}	Predicted v. of surf. sandwich layer deviation K_{CP}	Predicted value of homogeneous sandwich layer thickness rate K_{HP}	Predicted value of mean square error R^2
12	0.38	0.18	0.26	0.37	0.17	0.28	0.045
13	0.36	0.16	0.37	0.34	0.16	0.39	0.032
14	0.34	0.15	0.46	0.31	0.14	0.48	0.029
15	0.48	0.21	0.07	0.47	0.22	0.05	0.121
16	0.47	0.22	0.06	0.47	0.22	0.05	0.009
17	0.47	0.21	0.07	0.47	0.22	0.05	0.117
18	0.48	0.24	0.05	0.49	0.23	0.04	0.115
19	0.47	0.21	0.07	0.46	0.23	0.07	0.009
20	0.44	0.19	0.13	0.44	0.20	0.12	0.045

where: $R^2 = \sqrt{\dfrac{\left(\dfrac{K_{SP}-K_{ST}}{K_{ST}}\right)^2 + \left(\dfrac{K_{CP}-K_{CT}}{K_{CT}}\right)^2 + \left(\dfrac{K_{HP}-K_{HT}}{K_{HT}}\right)^2}{3}}$

Tab. 3 displays the comparison of predicted value from the prediction model and measured value of Panel 12 to Panel 20 in Tab. 1. It could be seen that the mean square error of predict value and measured value was within 13 %, so the model predict well, especially matched the U-FBs of higher homogeneous sandwich layer thickness rate best. When the preheating temperature was lower, time is shorter and moisture content is lower, the deviation of predict result and measured value was larger. That's because under such conditions, effect of preheating was worse which was affected by other factors easily, leading to the worse effect of model.

CONCLUSIONS

1. The ideal H-FBs could be produced under "pretreatment-hot pressing" united technology in which mats are preheated to 80°C and pre-pressed to target thickness; The average density and mat moisture content have little effect on the shape of VDP of H-FBs.
2. Surface humidification treatment could be adopted to eliminate pre-curing layer.
3. In the preheating and pre-pressing process, sandwich layer temperature is positively related to themat moisture content, preheating temperature and preheating time, while makes little difference in the average density. Prediction model of temperature within mats in the preheating and pre-pressing process can be established with pretreatment parameters composed of mat moisture content, preheating temperature and preheating time.
4. The united technology adopting pre-pressing, preheating, surface humidification and hot-pressing could be used to produce U-FBs. The shape of VDP of U-FBs can be quantified by the three factors as surface density deviation, sandwich layer density deviation and homogeneous sandwich layer thickness rate.

5. The VDP predict model under united technology can be established based on the relationship model of shape factors of VDP, sandwich layer temperature after pre- treatment and pretreatment parameters, which has a very strong predictive ability.

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