Investigation of drying characteristics in superheated steam drying of UF-impregnated Chinese fir

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Abstract

Urea formaldehyde (UF) resin-impregnated Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook.) was dried at different temperatures in an atmospheric pressure superheated steam dryer. Drying characteristics, moisture content, drying rate, temperature profile, drying defects, and color change were investigated. The moisture content was reduced from 66.21 to 11.79% within 30 h without causing severe drying defects; in contrast, the conventional hot air process required 7–8 days. After 25 h of drying, the temperatures at both the center and the surface of wood remained stable. After 34.5 h, the surface temperature gradually approached the steam temperature. The color of the superheated steam dried Chinese fir appeared slightly more intense yellow and red than the control. Investigation of the UF-impregnated Chinese fir wood by scanning electron microscopy (SEM) revealed that the majority of the lumens and voids, including the microvoids in wood structure, was filled with urea formaldehyde resin.

1 Introduction

The major concerns in timber are variations in final moisture content (MC), drying rate, warp, internal and surface checking, and discoloration. Wood from fast growing plantation forests shows variations in these properties. Defects in drying are a result of using juvenile wood, which is a serious problem. Presently, the conventional method of drying uses hot, moist air as the drying medium. Extensive research is being carried out to obtain optimum drying schedules by manipulating the temperature, humidity, and velocity of the air. After several days of drying, a mist of water droplets is introduced into the drying chamber and is circulated using fans. This method helps to distribute the moisture evenly and reduce moisture stress by temporarily increasing the relative humidity inside the chamber. If the temperature of the dryer is too high, the internal moisture stress may lead to cracking, due to large gradation in moisture content within the board (Kretschmann and Green 1996; Yi et al. 2004; Matan

and Kyokong 2002). The drying time varies from 7 to 16 days, depending on the thickness of the lumber. Rapid drying leads to drying defects, whereas slower drying increases the operational costs.

Wood drying is one of the most important steps in solid wood processing. To the best of the authors' knowledge, most of the relevant research concerned with wood products such as UF-resin impregnated Chinese fir plywood or some artifacts, the drying behavior of Chinese fir wood modified by UF resin has not been extensively studied. Superheated steam drying has gained tremendous interest in industrial applications such as drying of paper, food products, and coal. Earlier studies have illustrated some advantages of steam drying (Stubbing 1999; Chen et al. 2000; Pang and Pearson 2007), which include high drying rates in the case of both, constant and falling periods, as well as deodorization (Ratnasingam and Grohmann 2015). At a very high drying temperature, the wood temperature is above the boiling point of water (100 °C), which significantly enhances the flow of moisture in the wood interior (Tarnawski et al. 1996; Aly 1999; Vazquez et al. 2001; Bekhta and Niemz 2003). Pang and Dakin (1999) studied the drying rates and temperature profiles for both superheated steam vacuum drying and moist air-drying of softwood lumber (*Pinus radiata*), finding that superheated steam produced a significantly faster drying effect than hot moist air. Compared with conventional kiln drying, superheated steam drying has the potential to

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improve the quality of wood and to reduce energy consumption. The use of superheated steam for drying stimulates continuous heating, alleviating the need for alternative heating (Alvarez Noves and Fernandez-Golfin 1994). Another benefit of superheated steam drying is that evaporated steam is exhausted and condenses during the process (Yang et al. 2013), whereas in conventional hot air drying, the exhausted hot air undergoes heat loss due to drying.

The main objectives of the present work were to study the utilization of superheated steam for drying urea formaldehyde (UF) resin-impregnated Chinese fir and to investigate the drying characteristics in terms of instant drying rates and temperature profiles. This research provides a better understanding of drying characteristics of superheated steam and explains how drying medium influences the drying qualities. The drying characteristics of superheated steam drying were compared with those of hot air, aiming at promoting the transfer of drying technology from research into manufacturing practice.

2 Materials and methods

2.1 Materials

Fresh Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook) timber was collected from the Jiangxi Province, China for wood sample and was then impregnated with urea formaldehyde resin (molecular weight 8000 Da, solid content 25%). The Chinese fir was 13 years of age, had a diameter of 12.3 cm at breast height set to 1.5 m, and was characterized by an initial average moisture content (MC) of 78%. The fabrication of UF-modified wood was prepared in a pressure-processing tank. The vacuum pressure of the impregnation tank remained at 0.08 MPa for 20 min, then the specimens were added into the UF resin solution in the impregnation tank at a pressure of 0.6 MPa for 2 h. In parallel, the untreated group was kiln-dried until a target moisture content of 15%. Prior to use, the untreated and UF-modified timber were cut into the following dimensions: 200 mm (longitudinal) × 100 mm (tangential) × 20 mm (radial). Only the samples presenting a normal color with a straight grain and

no knots were selected for this experiment. The specimens were divided into two groups (6 replicates per group): the impregnated and the untreated group.

2.2 Drying characterization

The samples were checked for drying defects including end checks, end-to-surface checks, and surface checks at fixed time intervals during the drying process by visual appearance. Figure 1 is a schematic representation of the experiment using the superheated steam drying procedure. There are two temperatures and two mass flows associated with any portion of the wood area: superheated steam temperature of the inlet (T_i) and mass flow of the inlet (F_i); and superheated steam temperature (T_o) of the outlet and mass flow of the outlet (F_o).

During drying at 120, 130, 140, and 150 °C using superheated steam (flow rate of 125 m³/min), sample weights and wood temperatures were continuously measured and recorded. The drying procedure was continued until the moisture content of the wood was below 12%. The samples were periodically weighed on a meter balance (accuracy of ± 0.005). Temperatures were recorded from a digital reader, as shown in Fig. 2a. Thermocouples were placed at the surface and at the center of wood specimens to obtain the constant temperature profile recordings, as shown in Fig. 2b.

The drying rate for the sample was obtained by measuring the weight of the wood board after each period of drying. The initial moisture content of the wood was calculated by cutting out a small portion of the board and drying it at 103 °C for 48 h.

2.3 Color change

Color changes of the samples dried using superheated steam at different temperatures and by conventional hot air drying were determined using color difference meter (WCS-S, NH310, Φ20 mm, Abarke Technology, Tianjin, China). The colors were represented as “ a^* ”, “ b^* ” and “ L^* ” values in the Hunter system (Vanclay et al. 2009). “ L^* ” represents the lightness, “ a^* ” represents the chromatic coordinates on red-green axis, and “ b^* ” represents chromatic coordinates

Fig. 1 Schematic representation of the superheated steam drying procedure

Fig. 2 **a** Temperature reader and **b** locations on the sample at which the thermocouples were placed: surface (I) and center (II)

on blue-yellow axis. The net change of color (ΔE) was calculated by the following equation (Eq. 1),

$$\Delta E = [\Delta L^2 + \Delta a^2 + \Delta b^2], \quad (1)$$

where ΔL is the difference in lightness, Δa and Δb are the differences in red-green coordinates and blue-yellow coordinates, respectively.

Scanning electron microscopy (SEM) was used to study the depth and uniformity of penetration of the UF resin inside the impregnated Chinese fir. The internal structure and radial wall were also examined. The dried samples were cut into small specimens by using a sliding microtome (Leika, ESM-100L, Japan) to obtain a size of 10 mm × 10 mm × 5 mm (longitudinal × radial × tangential) for the SEM observations. The specimens were mounted on aluminum

stubs, sputter coated, and analyzed on microscope (Questar, 450 Quanta™, Hillsboro, USA) operating at an accelerating voltage of 15 kV.

3 Results and discussion

3.1 SEM

Samples for SEM were cut from the sample center to study the penetration and distribution of the UF resin within the wood sample, as previously described (Bolton et al. 1988). SEM images of radial walls of the control and specimens on the cross direction subjected to superheated steam drying at 120, 130, 140, and 150 °C are shown in Fig. 3. The

Fig. 3 SEM images of the control and UF-impregnated Chinese fir subjected to superheated steam drying at different temperatures

majority of the lumens and voids, including the microvoids in the wood structure, were filled with urea formaldehyde resin. This observation suggested that pressure impregnation successfully replaced the interior water molecules with the resin and produced a satisfactory bulking effect. The resin penetrated the cell walls, lumens, and intercellular spaces of wood, with maximum penetration in the cell walls.

3.2 Drying defects

During drying, three main types of drying defects (initial checks, internal checks, and cross-sectional deformations) were recorded and are listed in Table 1. The numbers in the table (in the initial check and internal check columns) signify the drying defects rank. Almost every sample had light end checks in initial stages. As the tests proceeded, the end checks became larger, and some of them transformed into end-to-surface checks and surface checks. Subsequently, checks kept developing until the moisture content was reduced to approximately 30%. After reaching a moisture content of 30%, these initial checks stopped stretching and began to cure, and the end checks closed in later stages.

3.3 Color change

In addition to drying defects, color changes during the drying of Chinese fir were also considered. In general, the Chinese fir underwent a change in its color either due to fungal

attack or due to oxidation during conventional drying. Pure steam, devoid of oxygen, provided an inert atmosphere during the superheated steam drying process in the dryer, which prevented the oxidation of wood, which minimized the chances of oxidation and helped to retain the color of dried wood similar to fresh wood. Table 2 presents the colors and lightness values of the superheated steam dried UF-impregnated Chinese fir samples (tangential direction) and the control group. The values of a^* , b^* , and L^* at the beginning of the experiment were -0.33 , -1.13 , and 33.14 , respectively. The L^* values of the samples subjected to superheated steam drying were slightly lower than the control, whereas the values of a^* and b^* increased. However, the net changes in product color (ΔE) were not remarkable for samples dried at 120, 130, 140, and 150 °C. The values for net color changes were slightly higher than those of untreated ones. This result implied that the dried Chinese fir showed slightly more intense yellow and red colors after superheated steam drying compared with untreated Chinese fir.

3.4 Drying rates

The moisture contents of the samples in superheated steam drying experiments at the temperatures of 120, 130, 140, and 150 °C are shown in Fig. 4. The results suggested remarkably lower moisture contents of the samples at higher superheated steam drying temperatures at corresponding time intervals. Generally, the curves depicting drying consisted of three distinct periods: (1) initial heating period; (2) constant drying period; and (3) falling rate period. The initial period, characterized by a rapid increase in temperature of the wood from room temperature to 100 °C, could not be clearly seen in this figure, as this time frame was small compared with the total drying time.

The drying periods for reducing the moisture content to ideally 12% were approximately 44.5, 36.5, 35.5, and 28.5 h for superheated steam temperatures of 120, 130, 140, and 150 °C, respectively. Although at 150 °C the drying period

Table 1 Drying defects after superheated steam drying

Drying defects (°C)	Initial check	Internal check	Cross-sectional deformation (mm)
120	1	1	0.54
130	1	1	0.60
140	3	–	0.99
150	2	–	1.07

Table 2 Color changes and values of L^* , a^* , and b^* for superheated steam dried samples at different temperatures

Samples	L^*	a^*	b^*	ΔE
120 °C	41.93	6.97	14.85	19.6
130 °C	42.32	6.07	14.57	19.3
140 °C	41.00	6.06	15.02	19.1
150 °C	42.87	5.67	13.53	18.3
Control	43.71	5.72	12.52	18.6

Mean values from 200 measurements.

Fig. 4 Moisture content of samples dried using superheated steam at different temperatures

for reducing the moisture content to the desired level was the shortest, it was not preferred because its surface color deteriorated (slightly brown), and the drying defects (especially initial and internal checks) were severe. The drying time for reducing the moisture content to the desired level is approximately 70 h at a temperature of 120 °C in conventional hot air drying (Pang and Dakin 1999). Thus, there was a 36.43% reduction of drying time by using superheated steam instead of conventional hot air at the same temperature.

Figure 4 shows that the drying rates of superheated steam were much higher than hot air, which took 7 to 8 days to reduce the moisture content of the wood to the acceptable value of less than 15% (Pang 1996, 2000). This was due to the impingement process (Peng et al. 2012), which caused rapid heat transfer to the wood surface and stimulated a quick loss of moisture (Li et al. 1999; Ishikawa et al. 2004). However, hot air drying at a constant rate gave faster results than that of superheated steam, due to lower humidity inside the chamber. After 28 h of superheated steam drying at 120 °C, the rate of water loss from the dried sample was quite low, due to a large quantity of water vapor present inside the chamber. Because the rates of water vapor leaving the vent and vapor condensing into liquid water were lower than that entering it, the internal humidity remained relatively high. This made the removal of bound water somewhat difficult. Hence, it was necessary to reduce the humidity inside the chamber to further reduce the final moisture content of impregnated wood.

Figure 5 compares the drying rates of wood samples using superheated steam and hot air conditioning. Initially, in both cases, the drying rates were relatively high because of the high concentration of water in the cells of wood present at the surface, thus allowing water to be removed readily. The drying rate decreased almost linearly as the moisture

Fig. 5 Drying rates of superheated steam drying and hot air drying processes

content decreased. As the temperature of the drying process approached the boiling point (100 °C), the drying rate was lower for superheated steam than for hot air. The drying rate of superheated steam at 120 °C was 0.02 kg water/ (kg of dry matter min) with 51.82% MC, which was less than that of the hot air under similar conditions. However, the drying rates at 150 °C for steam and hot air were 0.07 and 0.05 kg water/(kg dry of matter min), respectively, with 42.35% MC. Based on these findings, superheated steam was more capable of removing water at higher temperatures, and the overall drying rates in the superheated steam were noticeably improved.

3.5 Wood Temperature

Figure 6 shows temperature profiles at the center and on the surface of the wood, which was dried at different steam temperatures. As mentioned earlier, the temperature in each group increased rapidly until the boiling point of water was reached. It was also clear that the temperature at the surface increased at a faster rate than at the center. The temperature at the surface reached 100 °C after 24.0, 18.0, 16.5, and 15.0 h at 120, 130, 140, and 150 °C, respectively, while at the center it took approximately 25.5, 21.0, 18.0, and 16.5 h to reach the same temperature.

Furthermore, after 25 h of drying, the temperatures at both the center and surface remained stable (slightly lower than the steam temperature). After 34.5 h of drying, the temperature at the surface gradually approached the steam temperature, which indicated that the water molecules were tightly bound to the cell walls of wood from the UF-impregnated Chinese fir.

In the superheated steam drying method, internal resistance for vapor movement was less than the hot moist air

Fig. 6 Temperatures at the center and at the surface of wood for superheated steam drying method

drying method, particularly at temperatures below 100 °C. Therefore, the surface of the wood board was expected to retain relatively high moisture content over a long period of time, during which the board dried at a constant rate. Because external mass-transfer in steam drying was much faster than that in hot air, the driving force for the moisture transfer (such as the difference in partial vapor pressure) was lower than that for the hot air when dried at the same rate (Schwartz and Bocker 2000; Thiam et al. 2002). In this manner, the surface of the board remained at a lower temperature. The lower surface temperature was not effective in increasing the heat supply (Pang 1997). However, it was successful in reducing the severe drying defects such as internal checking and discoloration to brownish stain.

The predicted drying schedule below 150 °C was applied to verify the process experimentally using a 2 m³ dryer. Finally, the drying characteristics (warp, internal checks and cross-section deformations, and drying velocity) of the UF resin-impregnated wood were in good agreement with the drying characteristics recorded when using the sawn timber standard (GB/T 6491–2012 2012), which requires the minimum drying grade as being second rank. In the practical drying process, a moisture detector would be inserted inside the timber to continuously record the moisture changes, providing the evolution of the drying stage. Therefore, this drying schedule is moisture-based.

4 Conclusion

Drying in an atmospheric pressure superheated steam dryer was carried out to study the drying characteristics of UF-impregnated Chinese fir. The drying characteristics, such as

moisture content, drying rate, temperature profile, defects, and color change were investigated.

SEM showed that a majority of the lumens and voids within the wood structure were either filled and/or covered with UF resin. The drying time could be reduced remarkably by using superheated steam, without causing severe drying defects. Drying time could be reduced from 7 to 8 days to less than 2 days, which would considerably reduce the operational costs. After 25 h of drying, temperatures at both the center and the surface remained stable. After 34.5 h, the surface temperature gradually approached the temperature of the steam.

Moreover, the wood color was not remarkably affected by superheated steam drying. There was no apparent color difference, and the values of the net color change ΔE for the treated samples were slightly higher than the control group. Further studies are needed to clarify the role of UF resin in superheated drying process.

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