



## Effects of removal of different chemical components on moisture sorption property of *Populus euramericana* Cv. under dynamic hygrothermal conditions



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### ABSTRACT

Effects of chemical components on wood sorption property under dynamic condition were investigated for the first time. Hemicellulose, lignin and extractive (denoted as DHC, DL and DE, respectively) were removed from *Populus euramericana* Cv., 20 mm in radial (R) and tangential (T) directions with thickness of 4 mm along the grain, then the wood was subjected to cyclic tests where relative humidity (RH) varied from 45% to 75% sinusoidally at 25 °C. Based on measured data automatically, the results showed that, various chemical components had different effects on dynamic sorption behaviors of wood. The DL exhibited the largest moisture content and diffusion coefficient, followed by the DE, Control and DHC. This indicated lignin or extractive removal accelerated the dynamic sorption process and improved hygroscopicity of wood, while hemicellulose removal caused opposite effects. Theoretical sorption model was further applied and the modeled curves fitted satisfactorily with experimental data. Dynamic moisture gradient distribution inside the different treated wood was investigated and amplitude of moisture showed negative relation with wood element depth, while phase lag presented an opposite trend. Amplitude of DL was the largest while its phase lag was the least. Conditioning thickness for RH was greatest for DHC, about twice as much as the minimum of DL.

### Introduction

Wood, as one of the environmental friendly natural materials, has been widely used in our daily life for its characteristics of color, pattern, sound absorption, etc., especially the RH conditioning function, provided by that wood is ceaselessly exchanging water with atmosphere, since it follows the ambient relative humidity of the air due to the hygroscopic nature. This in turn brings about the continually changing moisture content (MC) in wood, and some defects such as cracking and warping may be caused, influencing wood using and processing.

Therefore, moisture sorption and wood conditioning function are important information [1,2], worth studying for the daily application and processing of wood or wood products.

Focusing on this, some studies were conducted and found moisture sorption could be affected by many factors, such as wood own composition, including cellulose, hemicellulose, lignin and extractive [3–8]. Cellulose and hemicellulose are rich in free hydroxyl groups, which could make great contribution to the hygroscopicity of wood, whereas lignin is a relative hydrophobic heteropolymer, composed by phenyl propane unit through carbon-carbon bonds or ether bonds [3,9–10]. As

a result, some studies showed that delignification could weaken the water resistance capabilities of wood. Removing the extractive will encourage wood sorption due to the fact that extractive deposit in cell cavity which could block the passage for water [4]. Studies have shown that heat treatment can effectively reduce hygroscopicity, moisture uptake rate [11], and sorption hysteresis, which could mostly be ascribed to the degradation of hemicellulose. Some researchers also believed that other chemical components of wood such as lignin played an important role in wood hygroscopicity [12].

Hosseinaei et al. [13–14] found that the hygroscopicity of wood-plastic composites decreased as temperature increased because more hemicellulose was removed at higher temperature. Ou et al. [9] pointed out that the delignification wood-plastic composite had the largest hygroscopicity and swelling, followed by the matrix removal group, extraction group, hemicellulose removal group. In 2014, Zhou et al. investigated the effect of removing chemical components of lignin and extractive on equilibrium moisture content (EMC) of *Cunninghamia lanceolata* Hook wood [10], and indicated the hygroscopicity of delignification wood was larger than the wood with extractive removal.

In addition, wood sorption property could also be affected by the

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outside RH. In 1988, Skaar indicated that the EMC was approximately proportional to ambient RH and pointed out that the RH where the wood exposed was the most significant factor affecting EMC [15,16]. The relation between EMC and RH at constant temperature is generally displayed by a curve named as sorption isotherm [17–20]. From the sorption isotherm, it is obvious that the EMC of wood increases with increasing RH at a given temperature.

However, the experiments above were conducted under static conditions, where RH and temperature were kept constant, while the atmospheric RH or temperature during wood processing and use is always changing and may be sinusoidal [21]. Therefore, it is quite very necessary to study the wood sorption and effect of chemical components removal under this dynamic condition, which is close to daily use condition of wood.

Chomcharn and Skaar [22] firstly conducted such work that dynamic sorption and hygroexpansion of wood wafers were studied where RH changed cosinusoidally at a constant temperature. Later in our previous studies, the moisture and tangential (T) and radial (R) dimensional changes of wood subjected to sinusoidal RH variation at a constant temperature [23] and square temperature variation at a constant RH [24] were investigated. However, these studies concentrated more on studying the wood sorption but little concern had been paid to its relationship with chemical components of wood.

In terms of wood sorption rate, moisture sorption kinetics could be considered as a method. Fick's second law was always been taken as the basement to build moisture sorption kinetics equation, which regarded the diffusion controlled the movement of wood interior, so that the moisture sorption could be simulated accurately. Stamm [25] explored Fick's diffusion law dealing with the sorption process and illustrated they do not adequately describe moisture movement in small wood specimens, other processes in addition to Fickian diffusion operate to limit the rates of moisture change in wood [26–30]. Christensen and Kelsey [26] studied the rate of water vapour adsorption by small specimens of Klinkii pine in the absence of air and found the sorption rate decreased as the moisture content increased. Kelly and Hart [27] measured the rate of water vapour adsorption and desorption of yellow poplar and white oak. An empirical equation was derived to fit the experimental data, but only limited success was achieved in relating the constant of the equation to the corresponding relative humidities. In 2010, Ma obtained the moisture sorption kinetics equation by combining the surface sorption theory with Bradley sorption theory. This model suggested that wood adsorption rate was related to the rate at which sorption spaces could be made accessible to water molecules rather than the classical Fickian behavior. And the moisture diffusion coefficient  $D$  in the model could be affected by species, density, MC, etc. [23]. Stamm [25] found  $D$  increased as MC increased and the exponential relationship could be established at the range from 5 to 25% MC, and from thence the  $D$  could also be influenced by wood chemical components for which could make significant contribution to MC.

Wood sorption behavior could not just be influenced by the outside atmospheric RH but also affected the atmospheric RH, that is the wood conditioning property. Many researchers found wood conditioning property was superior to other materials. And wood could mitigate the indoor surrounding RH rapid change [31–32]. Nevertheless, it also could be affected by many factors, such as wood species, thickness, amount of usage, wood isotherms, hygroscopic isobar, and the non-equilibrium moisture movement [33–34].

However, the conditioning process was conducted by wood adsorbing and desorbing water in atmosphere, and this wood sorption property could be affected with wood chemical composition, so that the wood conditioning property also could be influenced by wood chemical components. Nonetheless, there is few studies focused on that currently, especially in the dynamic condition.

The objective of this study is to investigate the effects of removal of different chemical components on wood sorption as well as the conditioning property under dynamic condition for the first time. The

results should be helpful in figuring out the effect from different chemical components on wood sorption and enriching the fundamental understanding of the sorptive behavior of wood at non-equilibrium state theoretically, and providing improved technical parameters for the conditioning property of wood products in service practically.

## Experimental

### Materials

Poplar (*Populus euramericana* Cv.) wood from the Greater Khingan Mountains in China was taken as study species with the average annual ring width of 3.5 mm and air-dried density of about  $0.4 \text{ g cm}^{-3}$ . The specimens were cut from clear, flat-sawed sapwood into the size of 20 mm in both R and T directions with thickness of 4 mm along the grain.

### Chemical treatment of wood

The specimens were divided into four groups according to their pretreatments, including untreated (Control), extractive removed (DE), hemicellulose removed (DHC), and lignin removed (DL). Later the four groups were all boiled in distilled water for 15 min to remove their growth stress. Then they were air dried then dried at  $80^\circ\text{C}$  until a constant weight ( $m_0$ ) was achieved.

After this, they were chemically treated as followed:

Extractive removed: extractives in wood were removed by ethanol-benzene extracted method [35,36]. The ethanol and benzene (1:2 vol ratio) (Beijing Chemical works Co., Ltd) were mixed, and the specimens were immersed in the mixture for 48 h then boiled for 3 h at  $60^\circ\text{C}$  in the same solution heated by water bath to remove soluble extractive. After that, they were washed with distilled water for 24 h, air-dried for 48 h, and finally dried at  $80^\circ\text{C}$  until a constant weight ( $m_1$ ) was achieved [35,36].

Hemicellulose removed: the DE was further extracted by liquid hot-water at  $170^\circ\text{C}$  in a reactor for 2 h with a water-to-solid ratio of 20:1 (w/w) and then washed with distilled water for 24 h, air-dried for 48 h, and finally dried at  $80^\circ\text{C}$  until a constant weight ( $m_2$ ) was achieved [13,14].

Lignin removed: the DE was firstly delignified with a mixture of 967 ml of distilled water, 20 g of  $\text{NaClO}_2$ , and 13 ml of  $\text{CH}_3\text{COOH}$  (Beijing Chemical works Co., Ltd) for decompression treatment for 5 h and then put into a water bath for 30 h at  $40^\circ\text{C}$  and then washed with distilled water for 24 h, air-dried for 48 h, and dried at  $80^\circ\text{C}$  until a constant weight ( $m_3$ ) was achieved [10,37].

### Measurement of dynamic moisture sorption of wood

After chemical treatments, the four groups were conditioned in 45% RH at  $25^\circ\text{C}$  controlled by saturated salt solutions of sodium chloride [38] purchased from Beijing Lanyi Chemical Products Co., Ltd, respectively over 10 days to obtain equilibrate weights. Afterwards, the specimens were moved into a conditioning oven (DHS 225, YaShiLin Co., Ltd, Beijing) to conduct the cyclic tests as described in Fig. 1. The RH (sensitivity  $\pm 1\%$ ) and temperature (sensitivity  $\pm 0.5^\circ\text{C}$ ) in the oven were programmed to vary in discrete steps according to predetermined schedules, and a thermo-recorder (TR-72Ui, Tandd Co., Ltd, Japan) was placed near the specimens to monitor the RH and temperature. During the processes, weight changes were measured by an electronic analytical balance (ME104E, Mettler-toledo Co., Ltd, America) (sensitivity  $\pm 0.1 \text{ mg}$ ) [19]. And the measured data could be recorded automatically by personal computer without opening the door of the conditioning oven throughout the dynamic tests. To control the changing frequency of RH, three sinusoidal cyclic periods were designed: 1) for 1 h cyclic period, a sinusoidal change completed in 1 h. One test contains 10 cycles, and last for 10 h. Measurements took at

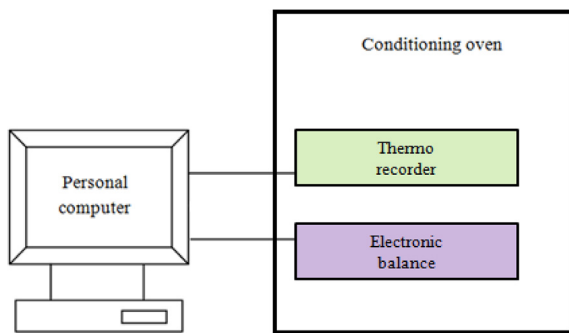


Fig. 1. Diagram showing the instrumentation for the entire assembly.

every 1 min. 600 data were collected for each parameter in one test; 2) for 6 h cyclic period, a sinusoidal change completed in 6 h. One test contains 6 cycles, and last for 36 h. Measurements took at every 5 min. 432 data were collected for each parameter in one test; 3) for 24 h cyclic period, a sinusoidal change completed in 24 h. One test contains 4 cycles, and last for 96 h. Measurements took at every 15 min. 384 data were collected for each parameter in one test.

In addition, there were three end-matched replicates for each cyclic period. Each test was repeated three times, and average values of the three tests for weights ( $m_4$ ) of the specimens were taken as the final result.

Fig. 2 presents a diagram for the whole experimental design.

The ratio of extractive loss ( $P_1$ ), hemicellulose loss ( $P_2$ ), and lignin loss ( $P_3$ ) was calculated according to Eqs. (1)–(3)

$$P_1 = \frac{m_0 - m_1}{m_0} \times 100\% \quad (1)$$

$$P_2 = \frac{m_1 - m_2}{m_0} \times 100\% \quad (2)$$

$$P_3 = \frac{m_1 - m_3}{m_0} \times 100\% \quad (3)$$

Approximately 3% of extractive in DE and 9% of the hemicellulose in DHC were removed, each calculated based on the oven-dried weight ( $m_0$ ) of wood. In DL, lignin losses were 13%.

And the dynamic moisture content of control ( $MC_1$ ), DE ( $MC_2$ ), DHC ( $MC_3$ ), DL ( $MC_4$ ) was calculated according to Eqs. (4)–(7).

$$MC_1 = \frac{m_4 - m_0}{m_0} \times 100\% \quad (4)$$

$$MC_2 = \frac{m_4 - m_1}{m_1} \times 100\% \quad (5)$$

$$MC_3 = \frac{m_4 - m_2}{m_2} \times 100\% \quad (6)$$

$$MC_4 = \frac{m_4 - m_3}{m_3} \times 100\% \quad (7)$$

#### Theoretical model for dynamic sorption

The theoretical model for dynamic sorption of Ma et al. [23] which considered both surface moisture exchange through the air-wood interface and internal diffusion within wood was used in this study to investigate the dynamic moisture sorption. Moisture exchange on the wood surface is given by

$$m_i = m_{i-1} + a(h - \exp(K_2 K_1^{m_{i-1}} + K_3)) \Delta t$$

$$K_1 = 1.0327 - 0.000674T$$

$$K_2 = 17.884 - 0.1432T + 0.0002363T^2$$

$$K_3 = 0.16 \quad (8)$$

where  $m$  is MC (%),  $a$  is sorption rate constant ( $1/h$ ),  $h$  is RH for the

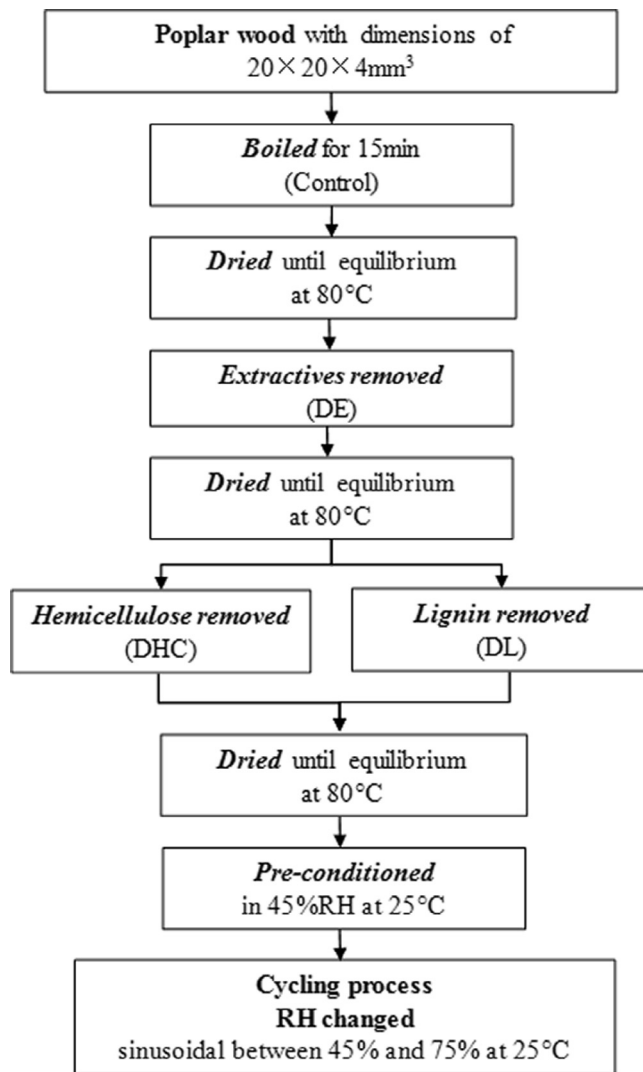


Fig. 2. Schematic diagram of experimental design.

surrounding atmosphere (%), and  $T$  is temperature (K).  $K_1$ ,  $K_2$ , and  $K_3$  are given by the Bradley equation [39], and their values were validated by experimental isotherm curves.

For the transfer of moisture inside the wood, a numerical solution by the finite difference method [37] for the Fick's second law was used.

$$m_{ji} = \frac{D(m_{j-i} - 2m_j + m_{j+1})_{i-1}}{\Delta l^2} + (m_j)_{i-1} \quad (9)$$

where  $D$  is the moisture diffusion coefficient ( $m^2/s$ ), the subscripts  $i - 1$ ,  $i$  are ordinal time points,  $j - 1$ ,  $j$ ,  $j + 1$  are ordinal elements in thickness direction, and  $\Delta l$  is the thickness of each element (m). The specimen in this work was divided into 7 ordinal elements along thickness direction as the 1 (surface), 2, 3, and the 4 (center) from surface to center, just as shown in below Fig. 3.

The value of  $D$  in Eq. (5) was taken as a constant in the previous study. However, in the present case, it is considered to be MC-dependent and expressed by an exponential function in longitudinal direction [14].

$$D = 0.40 \times 10^{-7} \exp(0.11m) \quad (10)$$

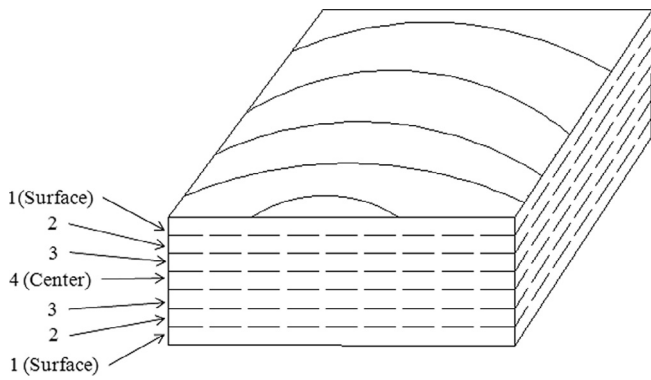


Fig. 3. Schematic diagram of ordinal elements in specimen thickness direction.

**Results and discussion**

*General moisture responses*

General MC responses of poplar wood with different components removal partly to the sinusoidal RH changes in the cyclic period of 24 h, as an example, is shown in Fig. 4. Obviously, MCs of four wood change sinusoidally, but all data show a certain phase shifts with sinusoidal RH change.

Table 1 summarizes the average MC in the 3 cyclic periods of poplar wood, which were subjected to different treatments of various components removal partly. Generally, the measured data all shows positive relation to the cyclic period. This is because the wood could respond to the RH change more enough with longer cyclic period. In addition, the DL exhibits the largest MC changes, followed by the DE and then Control. And the MC changes of DHC are the lowest. This is because lignin is a hydrophobic heteropolymer [9–10], the delignified group DL was supposed to possess lower water resistance compared with the Control. And extractive would block water passage to certain extent, which can slightly restrain the moisture sorption of wood, while hemicellulose removal can greatly reduce wood hygroscopicity because of a dramatic loss in the quantity of exposed hydroxyl groups [3].

*Dynamic theoretical sorption modeling*

Fig. 5 displays a comparison of theoretical calculated MC with experimental results of differently treated wood cycled at 24 h as an example. As is shown, all the theoretical data calculated by the mathematical model as Eqs. (8) and (9) [23] fit satisfactorily with the experimental data. This suggests this mathematical model is effective in this dynamic study.

**Table 1**  
Comparison of average MC for poplar wood with different treatments at 3 cyclic periods.

Cyclic period (h)	Moisture content (%)			
	Control	DHC	DL	DE
1	8.02 (0.012)	6.24 (0.008)	8.87 (0.019)	8.37 (0.023)
6	8.24 (0.017)	6.32 (0.009)	10.05 (0.021)	9.22 (0.041)
24	8.66 (0.016)	7.04 (0.014)	10.58 (0.018)	9.81 (0.037)

Data provided as the average (standard deviation) per cycle from several replicate experiments.

The diffusion coefficient  $D$ , used in dynamic sorption modeling for specimen at three cyclic periods, was also calculated and listed in Table 2.

It's obvious that the diffusion coefficient grows up as cyclic period increases but less than the static value [26], and the  $D$  of DL was the largest, followed by DE, Control, and DHC. This indicates that DL has the highest sorption rate while DHC has the lowest, indicating lignin and extractive removal could accelerate the moisture diffusion rate while hemicellulose removal just led to the opposite effect. Moreover, there is a positive relation between  $D$  and moisture content of specimens when analyzing the Table 1 and Table 2, which agrees with the static results [4,25]. This indicated the effect from chemical components in wood on sorption amount was analogous with sorption rate.

*Dynamic moisture gradient distribution in wood*

The moisture gradient distributions inside wood at four typical time steps (adsorption origin (I), 1/4 adsorption (II), 1/2 adsorption (III), terminal adsorption (IV)) during the adsorption and desorption processes of the second cycle at a period of 24 h, calculated according to theoretical Eqs. (8) and (9) [23], are shown in Fig. 6.

In the case of adsorption taking the DHC as an example, the time when the specimens just started to pick up moisture is about 1530 min. At this time, RH has already increased for about 90 min. However, as shown in this figure, moisture still takes on a regular shape of desorption distribution [40]. When adsorption time reaches 1710 min, about 1/4 of the adsorption process, the most relatively uniform distribution is obtained by the adsorption of the surface and desorption of the central part along the thickness direction of the specimens. At 1890 min, the midpoint of adsorption, the entire specimen began to sorb water, and a typical adsorption moisture distribution was found. Therefore, initially the central part of the specimens does not respond to the moistening. It takes about 6 h until the center part responds. Finally, MC reached the peak value at 2250 min, although RH had already

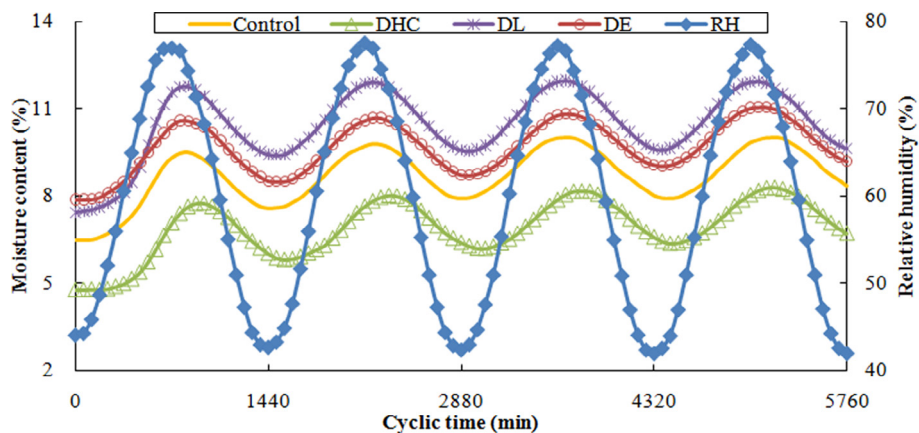


Fig. 4. Plots of moisture content changes where RH changes sinusoidally at a constant temperature against cyclic time for poplar wood with different treatments (cyclic period of 24 h).



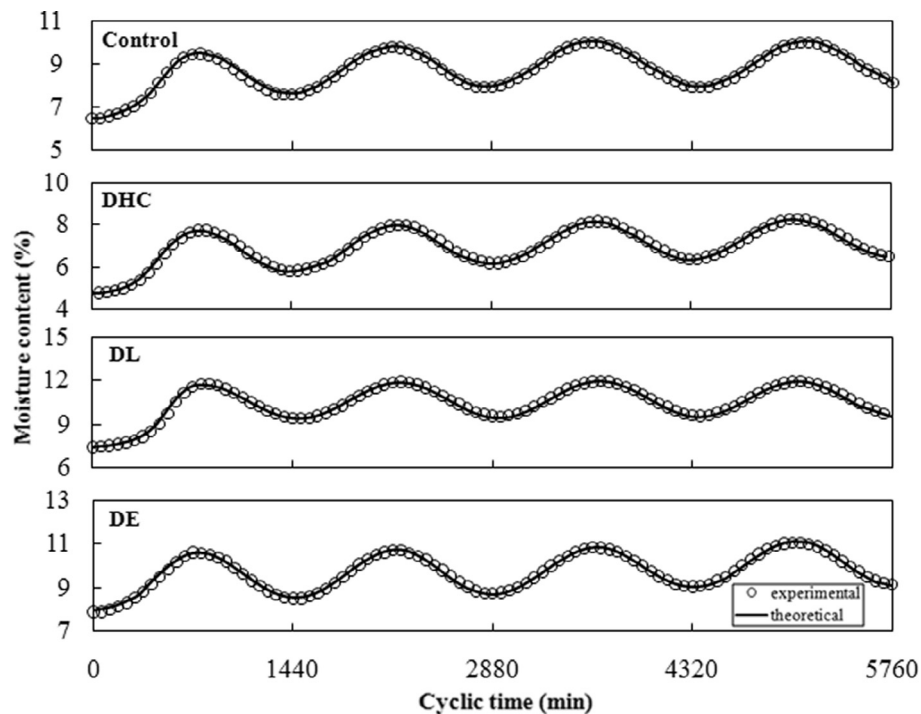


Fig. 5. Comparison of theoretical curves with experimental results of dynamic sorption for poplar wood with different treatments (cyclic period of 24 h).

**Table 2**

Diffusion coefficient  $D$  for poplar wood at 3 cyclic periods under dynamic conditions.

Cyclic period (h)	$D \times 10^{-11}(\text{m}^2/\text{s})$			
	Control	DHC	DL	DE
1	0.97 (0.012)	0.79 (0.010)	1.06 (0.024)	1.00 (0.018)
6	0.99 (0.021)	0.80 (0.013)	1.21 (0.033)	1.10 (0.023)
24	1.04 (0.020)	0.87 (0.16)	1.28 (0.034)	1.18 (0.019)
Static value	2.0 (at about 10% MC at 26.7 °C) [25]			

Data provided as the average (standard deviation) per cycle from several replicate experiments.

decreased. The moisture distribution difference at this time is less than that at 1890 min. Nevertheless, the moisture distribution is still far from equilibrium.

In addition, there are some differences caused by the chemical components removal. For instance, the least MC gradient difference between surface and central part was existed in DHC (0.70%) and then DL (0.96%), DE (1.04%) followed by control (1.09%). This could be due to the higher MC in central part in second adsorption process resulted from the larger phase lag (Section ‘‘Dynamic conditioning property of wood’’ for details) for DHC. In addition, the diffusion coefficient was larger for DL ascribed to its lowest lignin content than DE then Control, so that the moisture could reach the central part faster for DL than DE then Control, and the MC difference between surface and center for DL was less than DE then Control. Moreover, it is earlier for DL central part to begin adsorption process (1665 min) than DE (1680 min) then Control (1695 min) and followed by DHC (1710 min). Apparently, the maximum time difference existed between DL and DHC was 45 min. It could also assume that moisture distributions for desorption have the same tendencies as those for adsorption.

#### Dynamic conditioning property of wood

3.4.1 General MC of the element at different depths along thickness direction

Fig. 7 compares the moisture content changes of the surface, center elements along the thickness direction as well as the overall sample against cyclic time. It’s apparent that moisture content of different ordinal elements changes sinusoidally with various amplitudes and phase lags to imposed relative humidity, which are further displayed in Table 3.

#### Amplitude and phase lag

Amplitude and phase lag of the moisture changes are two parameters characterizing wood’s ability to respond to varying environment [19,41], both of which depend on the reaction time of the wood-water system. Herein, they could be used to evaluate the ability of different ordinal elements along the thickness direction of the specimen to respond to varying environment.

As is shown in Table 3, amplitude of wood increases as cyclic period increases, and it tends to decrease as element depth increases, that is, the amplitude of surface is the largest, while that of center is the lowest. The phase lag, on the other hand, shows opposite results with cyclic period and element depth. This could be explained by the fact that the surface was close to the atmosphere, thus less time was needed to respond to the environmental RH changes while the interior required more time to react. Furthermore, amplitude is larger for the DL then DE followed by Control while the DHC displays the lowest amplitude. Differently, compared with the Control, the phase lag tends to be less for DL followed by DE, and the phase lag of DHC was the largest This is because lower water resistance was possessed in DL and the water passage was opened in DE, therefore, the moisture change could more easily follow the environmental changes and respond more enough, while the free hydroxyl groups of hemicellulose removal in DHC could reduce the hygroscopicity and sorption rate in cooperation with the front Section ‘Dynamic theoretical sorption modeling’.

In addition, the amplitude of the overall is lower than that of the surface but larger than that of the other ordinal elements along the thickness direction. And the phase lag of the overall presents a reverse trend. This illustrates that there was greater effect from environmental hydrothermal condition on wood surface than interior in terms of wood sorption amount and speed. Besides, the amplitude in static condition

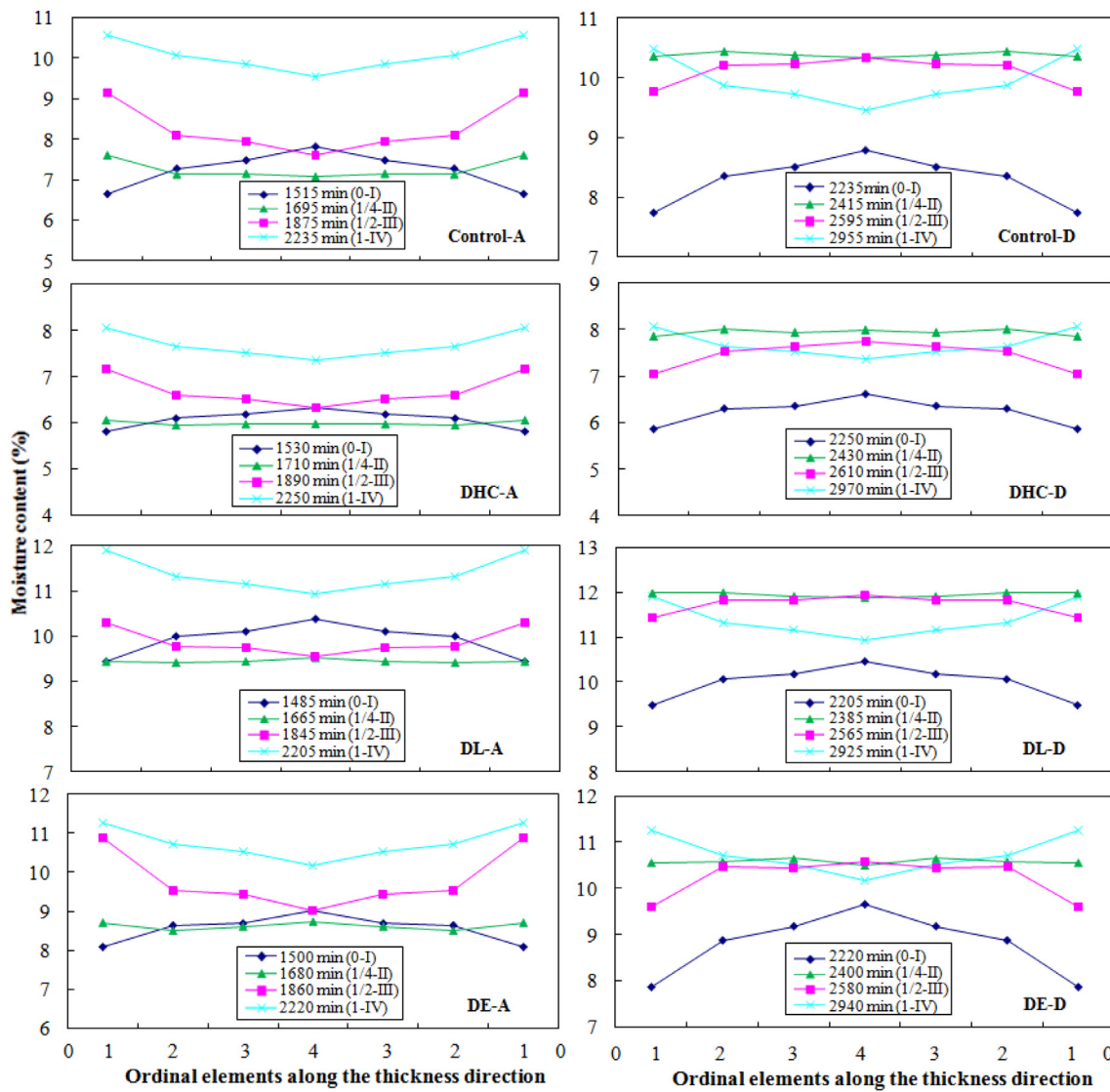


Fig. 6. Moisture distributions along the thickness direction of the samples treated differently for adsorption (A) and desorption (D) during the second cycle at cyclic period of 24 h.

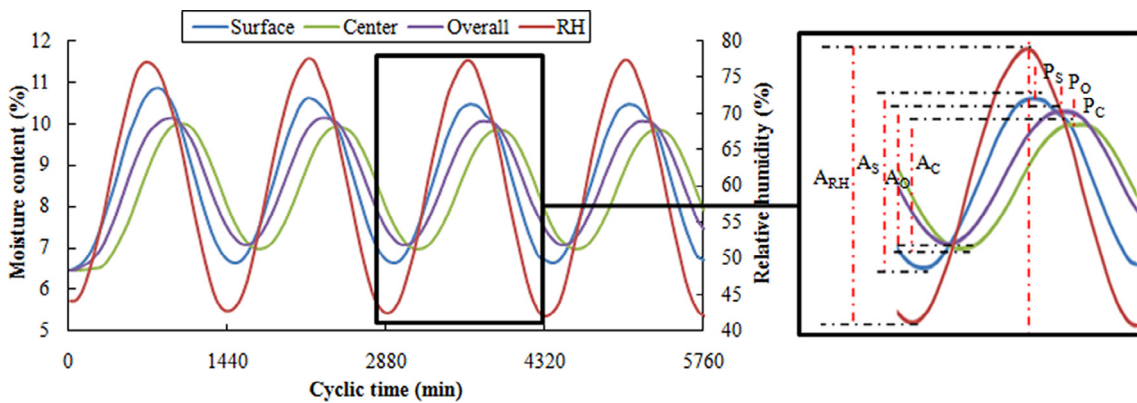


Fig. 7. Plots of moisture content changes of surface, center elements along the thickness direction and the overall sample for Control against cyclic time (cyclic period of 24 h) A: amplitude. P: phase lag. s: surface. c: center. o: overall.

was over two times of that in dynamic condition, while the amplitude difference between DL and the Control was 0.35% in dynamic condition, more than half of that in static condition, and the similar difference between static value and dynamic value could be found for DE and

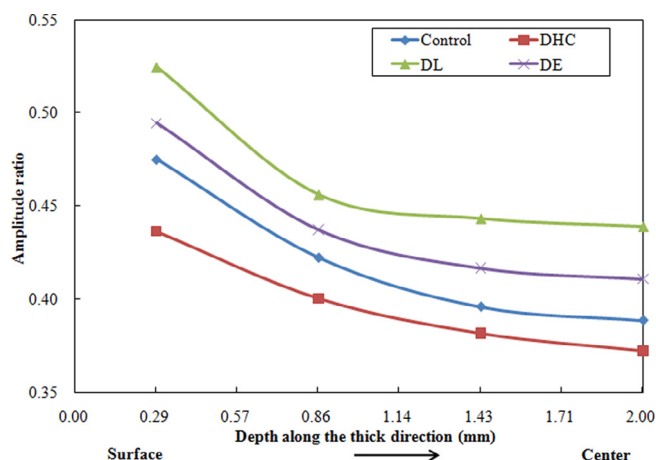
Control or DHC and Control. That is to say, the chemical components removal effect on wood sorption was larger in dynamic condition.

Amplitude ratio is one of the significant parameter to evaluate the wood conditioning property to atmospheric hygrothermal changes. The

**Table 3**  
Amplitude and phase lag of ordinal elements along the thickness direction and the overall sample subjected to different treatments under dynamic conditions.

Specimen	Cyclic period (h)	Phase lag (radian)					Amplitude (%)					
		1 Surface	2	3	4 Center	Overall	1 Surface	2	3	4 Center	Overall	Static
Control	1	0.16 (0.01)	0.93 (0.03)	1.13 (0.08)	1.15 (0.05)	0.49 (0.03)	2.62 (0.07)	2.40 (0.08)	2.25 (0.06)	2.16 (0.07)	2.38 (0.05)	6.17
	6	0.12 (0)	0.91 (0.02)	1.04 (0.02)	1.09 (0.04)	0.41 (0.02)	2.94 (0.16)	2.72 (0.11)	2.5 (0.09)	2.47 (0.12)	2.61 (0.09)	
	24	0.07 (0)	0.87 (0.02)	1.02 (0.03)	1.07 (0.03)	0.27 (0.01)	3.24 (0.11)	2.88 (0.13)	2.74 (0.14)	2.65 (0.09)	2.79 (0.10)	
DHC	1	0.17 (0.01)	0.98 (0.04)	1.19 (0.07)	1.22 (0.09)	0.64 (0.02)	2.49 (0.09)	2.36 (0.06)	2.13 (0.11)	2.04 (0.05)	2.27 (0.08)	5.72
	6	0.14 (0.01)	0.93 (0.02)	1.11 (0.08)	1.13 (0.07)	0.47 (0.01)	2.57 (0.12)	2.45 (0.02)	2.30 (0.06)	2.17 (0.04)	2.35 (0.11)	
	24	0.08 (0)	0.92 (0.01)	1.07 (0.04)	1.10 (0.04)	0.32 (0.01)	2.79 (0.11)	2.56 (0.05)	2.44 (0.10)	2.38 (0.07)	2.51 (0.12)	
DL	1	0.13 (0.01)	0.71 (0.02)	0.78 (0.02)	0.81 (0.05)	0.28 (0.02)	2.88 (0.17)	2.71 (0.11)	2.53 (0.12)	2.44 (0.09)	2.62 (0.10)	6.83
	6	0.09 (0)	0.69 (0.02)	0.76 (0.02)	0.78 (0.03)	0.23 (0.01)	3.46 (0.20)	2.98 (0.13)	2.64 (0.14)	2.55 (0.10)	2.87 (0.17)	
	24	0.03 (0)	0.67 (0.01)	0.72 (0.02)	0.73 (0.02)	0.18 (0.01)	3.68 (0.21)	3.20 (0.08)	3.11 (0.07)	3.05 (0.11)	3.14 (0.19)	
DE	1	0.14 (0.01)	0.83 (0.04)	0.98 (0.06)	1.01 (0.06)	0.42 (0.03)	2.78 (0.09)	2.57 (0.06)	2.36 (0.11)	2.23 (0.03)	2.52 (0.12)	6.51
	6	0.11 (0.01)	0.72 (0.03)	0.81 (0.02)	0.83 (0.05)	0.36 (0.02)	3.02 (0.12)	2.79 (0.04)	2.62 (0.13)	2.54 (0.02)	2.73 (0.14)	
	24	0.05 (0)	0.69 (0.02)	0.79 (0.03)	0.8 (0.04)	0.22 (0.01)	3.37 (0.08)	2.98 (0.07)	2.84 (0.15)	2.78 (0.04)	2.96 (0.18)	

Data provided as the average (standard deviation) per cycle from several replicate experiments



**Fig. 8.** Plots of amplitude ratio of different sample groups against the ordinal element depth along the thickness direction (cyclic period of 24 h).

**Table 4**  
Conditioning thickness of differently treated wood cycled at three periods.

Cyclic period (h)	Conditioning thickness (mm)			
	Control	DHC	DL	DE
1	0.86	0.86	0.57	0.86
6	1.14	1.43	0.71	1.00
24	1.43	1.71	0.86	1.14

ratio between the amplitude of MC curve in different positions of wood and that of the EMC curve achieved at the same RH and temperature is defined as the amplitude ratio [29].

Fig. 8 shows the amplitude ratio against the depth along the thickness direction of different sample groups cycled at 24 h. Apparently, the amplitude ratio of samples decreases firstly sharply then slowly, and later tend to approach a steady value, illustrating that wood has reached the state of effective conditioning in this depth [29]. However, the depth in the thick direction of different treated specimen is different when the steady value is achieved. As shown in Table 4, the conditioning thickness increases as cyclic period increases. This demonstrates larger effective conditioning thickness would be achieved with longer cyclic period.

In addition, the conditioning thickness varied with different treated specimens, namely, the chemical components have different effects on wood conditioning property. Apparently, the conditioning thickness is generally larger in DHC than Control and DE. The DL shows the lowest conditioning thickness, about half of DHC in the cyclic period 24 h,

illustrating the DL has reached the state of effective conditioning in this depth [29] and the DL wood has better conditioning property due to the removal of lignin.

### Conclusions

Effects of main chemical components in cell wall on dynamic moisture sorption of *Populus euramericana* Cv. were discussed for the first time by removing hemicellulose, lignin, and extractives respectively. The following conclusions could be attained: MCs of all wood also changed sinusoidally but lagged behind the triggering sinusoidal RH change. The DL exhibited the largest MC changes (10.58%), followed by DE (9.81%), Control (8.66%) and DHC (7.04%), indicating lignin or extractive removal could improve hygroscopicity of wood, while hemicellulose removal reduced wood hygroscopicity. The theoretical sorption model was applied and modeled curves agreed satisfactorily with practical experimental data. It was earliest for DL inferior to begin every sorption process, followed by DE, DHC and Control. Diffusion coefficient increased as prolonging cyclic period, and showing a similar variation trend to MC, suggesting lignin or extractive removal could accelerated dynamic sorption process, but hemicellulose removal caused the opposite result. Amplitude of different elements along thickness direction displayed positive relation with cyclic period but was inverse with depth, while phase lag displayed an opposite trend. Amplitude was larger for DL followed by DE, Control and DHC whereas phase lag showed an opposite trend. The conditioning property for RH was further discussed, and the conditioning thickness was greatest for DHC, about twice as much as the minimum of DL.

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### Conflicts of interest

The authors declare no conflict of interest.

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