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Original Article

Comparison of Dynamic Sorption and Hygroexpansion of Wood by Different Cyclic Hygrothermal Changing Effects[1]

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ABSTRACT

To investigate the dynamic sorptive and hygroexpansive behaviors of wood by different cyclic hygrothermal changing effects, poplar (*populus euramericana* Cv.) specimens, were exposed to dynamic sorption processes where relative humidity (RH) and temperature changed simultaneously in sinusoidal waves at 75-45% and 5-35℃ (condition A) and where RH changed sinusoidally at 75-45% but temperature was controlled at 20℃ (condition B), both for three cyclic periods of 1, 6, and 24 h. Moisture and dimensional changes measured during the cycling gave the following results: Moisture and transverse dimensional changes were generally sinusoidal. Moisture and dimensional amplitude increased with increasing cyclic period but all were lower for thicker specimens. The amplitude ratio of condition A to condition B ranged from 1.0 to 1.6 with the maximum value of 1.57 occurring at the shortest cyclic period, not as much as expected. T/R increased as cyclic period increased or specimen thickness decreased. T/R from condition B was weaker than that from condition A. Sorption and swelling hysteresis existed in both conditions. Sorption hysteresis was negatively related to cyclic period but in positive correlation with specimen thickness. Sorption hysteresis was found more obvious in condition B, while moisture sorption coefficient and humidity expansion coefficient showed the opposite results.

Keywords : dynamic sorption, hygroexpansion, relative humidity, temperature, wood

1. INTRODUCTION

Wood is continually changing in moisture content (MC) and dimensions during practical use due to changes in environmental humidity and temperature. These moisture variations inevitably produce dimensional changes in wood. Therefore, changes in dimensions that accompany the usual fluctuations of relative humidity and temperature are important considerations after wood has been placed in service.

In the literature, wood moisture and dimensional changes have been studied from various aspects, such as affecting factors including temperature, relative humidity, sorption history, hydrostatic pressure, chemical modification and so forth (Liu and Zhao, 2004; Ma and Zhao, 2012; Stamm and Loughborough, 1935;

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Kollmann, 1959; Weichert, 1963; Kelsey, 1957; Obataya, 2002; Stamm, 1964; Gong, 2001; Stevens, 1963; Espenas, 1971; Hill and Jones, 1999; Hill, 2008; Thygesen *et al*., 2010; Engelund *et al*., 2010; Hoffmeyer *et al*., 2011; Chang *et al*., 2012; Williems, 2014b; Seung *et al*., 2015; Park *et al*., 2015), moisture sorption theory (Dent, 1997; Brunauer *et al*., 1938; Simpson, 1973; Williems, 2015), sorption mechanism (Williems, 2014a; Urquhart, 1929; Chen and Wangaad, 1968; Engelund *et al*., 2013) and so on, which made great contributions to wood science.

However, these studies mainly concentrated on the moisture and dimensional changes under static condition where RH and temperature kept constant, which could simply the experimental process (Yang and Ma, 2013) and accumulate a certain basic data but was too ideal. In practice, wood were almost processed and used in atmospheric humidity and temperature which may be cyclic or sporadic, namely the dynamic condition. Therefore, studies in such conditions could be more practical to wood utilization.

It was Stevens (1963) who initially came to the study in dynamic condition. He proposed the term “movement” showing the dimensional changes of dried wood with atmospheric relative humidity changing, which is an important index to reflect the wood dimensional stability. And Farmer (1972) further indicated the method to evaluate the characteristics of wood “movement”. Then lots of studies were conducted to investigate the sorption and hygroexpansion behavior of wood with cyclic relative humidity (Harris, 1961; Arevalo, 2001; Wu and Lee, 2002; Fan *et al*., 2004; García *et al*., 2005; Olek *et al*., 2013).

Nevertheless, these researches were still developed based on the measurement at the beginning and end of cycles, which is the moisture equilibrium state. Therefore, it was limited to examine the behavior of wood response to environment during the cyclic process.

Until 1983, Chomcharn and Skaar (1983) firstly started to study the sorption and hygroexpansion of wood under dynamic condition. Later in a series of our studies (Ma *et al*., 2010; Yang and Ma, 2013), the moisture and tangential (T) and radial (R) dimensional changes of wood subjected to a sinusoidally varying RH were investigated, with different species and sample sizes.

However, we still fail to know exactly how much wood will react in practical condition from these studies where only RH changed at a constant temperature, because atmospheric RH and temperature during wood processing and use are both always varying which may be sinusoidal (Schniewind, 1967).

Therefore, based on the previous researches, the work presented here was conducted to investigate the effect of cyclic temperature and RH which both changed sinusoidally to become more closed to practical atmospheric condition changes on the dynamic sorption and hygroexpansion of wood. Furthermore, a comparison was made to discuss the difference between the hydrothermal treatment and the one only RH changed at a constant temperature.

The results should be helpful in enriching the fundamental understanding of the sorptive and hygroexpansive behaviors of wood at non-equilibrium, and providing technical parameters for the control in moisture and dimensional stability for wood products in service.

2. EXPERIMENTAL

2.1. Materials

Poplar (*Populus euramericana* Cv.) from the Greater Khingan Mountains in China was chosen as the study species.

2.2. Methods

The specimen sapwood, with the average annual ring width 3.5 mm, cut into 20 mm in both R and T directions with two thicknesses of 4 mm and 10 mm along the grain, was separated into two groups. The two groups were boiled in distilled water for 15 min to remove their growth stress at the beginning. Then they were oven-dried at 105℃ for 48 h, and oven-dried weights were measured. Later they were conditioned in 75% RH at 5℃ for the first group and 75% RH at 20℃ for the second group for 10 days, controlled by saturated salt solutions of Sodium chloride, respectively (Macromolecule Academy, 1958). Afterwards, the specimens were moved into a conditioning oven to conduct the cyclic tests, where RH cycled sinusoidally between 75% and 45% (sensitivity ± 1%), at sinusoidal temperature changes between 5℃ and 35℃ (sensitivity ± 0.5℃) at three periods of 1, 6, and 24 h for the first group (condition A) and RH changed in sinusoidal wave between 75% and 45% (sensitivity ± 1%), at a constant temperature of 20℃ (sensitivity ± 0.5℃) (the right middle temperature of 5-35℃ in condition A) for the second group (condition B) as shown in Fig. 1. The RH in the oven was programmed to vary in discrete steps according to a predetermined schedule, and a thermo-recorder was placed near the specimens to monitor RH and temperature. During the process, weight changes, as well as tangential (T) and radial (R) dimensional changes, were measured at every 1, 5, or 15 min time intervals for each of the three cycles, respectively, by an electronic analytical balance (sensitivity ± 0.1 mg) (Ma *et al.* 2010) and a self-made 2-dimension measuring system constructed by four CCD laser displacement sensors in Fig. 2 (sensitivity ± 1 μm). And the diagonal two CCD laser displacement sensors measured the dynamic T and R dimensional changes, respectively.

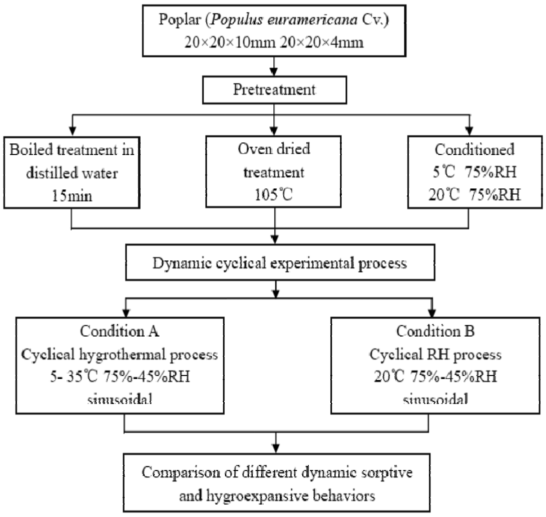
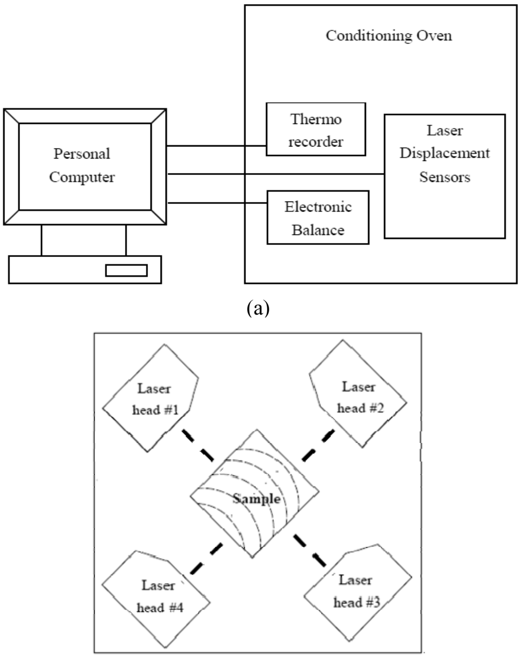


Fig. 1. Schematic diagram of experimental design.



(a)

(b)

Fig. 2. Diagram showing the instrumentation for (a) the entire assembly and (b) detection of dimensional changes in the sample, in which laser head 1 and 3 is for tangential measurement and laser heads 2 and 4 are for radial.

In addition, there were three end-matched replicates for each cyclic period, one for dimension and the other two for weight measurement. Each period was repeated three times, and average values of the three tests for weights and dimensions of the specimens were taken as the final result.

3. RESULTS and DISCUSSION

3.1. General Moisture and Dimensional Responses

Moisture and dimensional changes measured during the cycles gave such results as shown in Fig. 3. Moisture and dimensional changes of the specimens are generally sinusoidal for both condition A and B but behave in reverse trends with temperature in Fig. 3(a), namely, with a decrease in relative humidity and an increase in temperature, the moisture content becomes lower, and the dimensional changes decrease at the same time. Because a reduction in RH will trigger the desorption of wood (Liu and Zhao, 2004) and as temperature rises on the other hand, wood tends to lose water due to either the decreasing of sorption sites (Kelsey, 1957) or more evaporation of adsorbed water as a results of shifting to a higher potential energy (Liu and Zhao, 2004; Williems, 2014), as supported by static studies. It seems that dimensional changes were reflected as the effect of dehydrated shrinkage.

Table 1. Comparison of average MC for two thick poplar wood at 3 cyclic periods under different dynamic conditions

Thickness /mm	Cyclic period /h	MC/%	
		MC^{A}	MC^{B}
4	1	8.93 (0.014)	8.33 (0.022)
	6	9.64 (0.009)	9.11 (0.011)
	24	9.78 (0.012)	9.38 (0.037)
10	1	8.38 (0.031)	8.10 (0.054)
	6	8.52 (0.042)	8.35 (0.009)
	24	9.13 (0.024)	8.96 (0.011)

[A] Data provided with the average value of each specimen where both RH and temperature changed sinusoidally at 75-45% RH and 5-35℃

[B] Data provided with the average value of each specimen whereRH changed sinusoidallybetween 75-45% RH at 20℃ Data provided as the average (standard deviation)

Table 1 gives a comparison of average moisture content by different cyclic hygrothermal

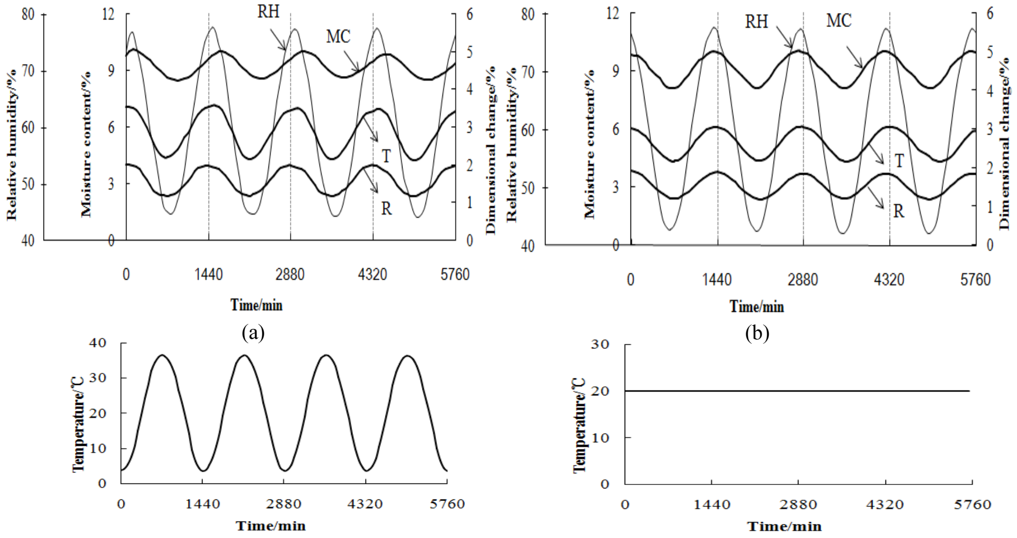


Fig. 3. Plots of moisture content (MC), tangential (T) and radial (R) dimensional changes where both temperature and RH changed sinusoidally (a) and where RH changed sinusoidally at constant temperature (b) against cyclic time for 10 mm thick poplar wood (cyclic period of 24 h).

treatments for 4 mm and 10 mm thick wood at three cyclic periods. It is clear that moisture content decreases as specimen thickness increases but increases with increasing cyclic period, which agreed with our previous study (Yang and Ma, 2013). In addition, the moisture content for condition A is slightly larger than that of B. This might be due to the superimposed effect of RH and temperature in condition A.

3.2. Amplitude

The amplitude of the moisture content and R and T dimensional changes is one of the parameters characterizing wood's ability to respond to varying environment, which depends on the reaction time of the wood-water system (Yang and Ma, 2015).

Table 2 presents the moisture and dimensional response amplitude from condition A and B for poplar wood. It is evident that the moisture amplitude as well as the dimensional response amplitude shows the same trend that both are greater for the specimens exposed to longer cycles for 4 mm and 10 mm thick specimens, which agrees with the results by Chomcharn and Skaar (1983). This is probably because there were relatively enough time for the specimens at longer cyclic period to response to the varying RH and temperature.

In addition, the moisture and dimensional amplitude are lower for thicker specimens. This was anticipated because there was not sufficient time for the thicker specimens, especially their inner part, to respond to the imposed RH and

Table 2. Amplitude of moisture content and tangential and radial dimensional changes for two thick poplar wood cycled at 3 periods

Thickness /mm	Cyclic period /h	Amplitude/%^{a}						Amplitude ratio		
		MC^A	T^A	R^A	MC^B	T^B	R^B	MC	T	R
4	1	2.47 (0.016)	0.78 (0.024)	0.40 (0.018)	1.57 (0.031)	0.59 (0.006)	0.32 (0.030)	1.57	1.32	1.25
	6	2.63 (0.011)	1.01 (0.015)	0.78 (0.010)	1.97 (0.003)	0.88 (0.009)	0.56 (0.023)	1.34	1.15	1.39
	24	2.68 (0.003)	1.12 (0.001)	0.83 (0.008)	2.59 (0.011)	0.98 (0.024)	0.77 (0.019)	1.03	1.14	1.08
10	1	1.25 (0.024)	0.69 (0.029)	0.34 (0.021)	0.84 (0.008)	0.44 (0.036)	0.22 (0.031)	1.49	1.57	1.55
	6	1.88 (0.019)	0.89 (0.054)	0.68 (0.031)	1.70 (0.021)	0.75 (0.022)	0.46 (0.002)	1.11	1.19	1.48
	24	2.14 (0.043)	1.03 (0.026)	0.74 (0.025)	1.97 (0.006)	0.87 (0.016)	0.71 (0.007)	1.09	1.18	1.04

$^{A, B}$ as defined above

Data provided as the average (standard deviation)

temperature changes. Moreover, compared with condition B, both moisture and dimensional amplitudes are greater in condition A. This might result from the combined effect of RH and temperature changes as described in section 3.1. Therefore, amplitude ratio of condition A to condition B was figured out and it could be found in Table 2 that the ratio generally ranges from 1.0 to 1.6. These values were not as much as expected from a superposition of both RH and temperature changing treatment. And the maximum value in the ratio of 1.57 is obtained at cyclic period of 1 h for moisture amplitude response, with a decrease against increasing cyclic period. All this indicates that the practical atmosphere would not double the moisture and dimensional responses of wood subjected to RH variations alone, but short cyclic period could aggravate the difference between them.

3.3. Transverse Anisotropy

T/R, the ratio of T dimensional change to R dimensional change during the cyclic process was worked out to discuss transverse anisotropy under different dynamic conditions.

Table 3 summarizes the T/R for 4 mm and 10 mm thick poplar wood cycled at three periods in two dynamic conditions. The T/R ratios are about 1.5 to 1.8 under these dynamic conditions, lower than the static results (Liu and Zhao, 2004). In addition, the T/R is generally in positive relation with cyclic period but inversely with specimen thickness, that is, T/R increases with increasing cyclic period and decreasing specimen thickness. This can be expected because T dimension reacted to dynamic condition faster than R direction according to our previous study (Yang and Ma, 2013), as a result, the difference between T and R re-

Table 3. Transverse anisotropy T/R for 4 mm and 10 mm thick poplar wood cycled at 3 periods under two dynamic conditions

Thickness/mm	Period/h	T/R^A	T/R^B
4	1	1.68 (0.003)	1.61 (0.008)
	6	1.73 (0.011)	1.71 (0.013)
	24	1.84 (0.009)	1.79 (0.017)
10	1	1.59 (0.029)	1.54 (0.041)
	6	1.65 (0.033)	1.60 (0.022)
	24	1.77 (0.010)	1.69 (0.016)

$^{A, B}$ as defined above
Data provided as the average (standard deviation)

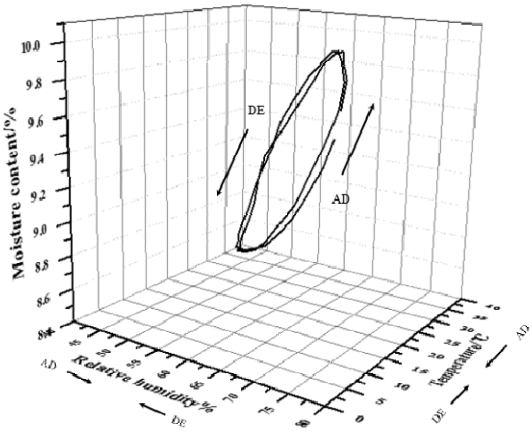
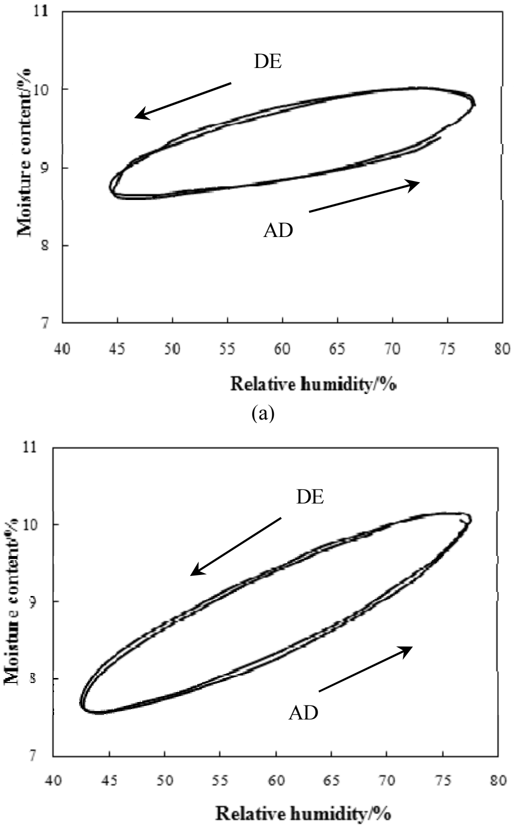


Fig. 4. Plots of dynamic moisture sorption curves against temperature and RH for poplar wood (10 mm, 24 h) AD: adsorption DE: desorption.

sponses would be more obvious with extending cyclic period, which directly leads to growing T/R. After a comparison, it can be found that T/R^B where only RH changed is less than T/R^A where both RH and temperature cycled. This is because the RH and temperature cooperated with each other and formed a superimposed effect on dimensional responses.



(a)

(b)

Fig. 5. Plots of dynamic moisture content changes with RH for poplar wood under condition A (a) and condition B (b) (10 mm, 24 h).

3.4. Sorption and Swelling Hysteresis

Dynamic moisture sorption of 10 mm thick poplar wood against temperature and RH cycled at 24 h is shown in Fig. 4 as an example for condition A, and Fig. 5(b) also gives the results for condition B as a control. Sorption hysteresis can be observed in both the figures. To compare both conditions quantitatively, the projection of MC-RH plane from the curve in Fig. 4 was made and displayed in Fig. 5(a). It's appa-

Table 4. Sorption hysteresis ratio A/D for poplar wood under different dynamic conditions

Thickness/mm	Period/h	A/D^{A}	Average^{A}	A/D^{B}	Average^{B}
4	1	0.88 (0.012)	0.91 (0.036)	0.86 (0.007)	0.89 (0.025)
	6	0.90 (0.009)		0.89 (0.002)	
	24	0.95 (0.004)		0.91 (0.001)	
10	1	0.86 (0.008)	0.89 (0.036)	0.85 (0.004)	0.86 (0.012)
	6	0.88 (0.010)		0.85 (0.010)	
	24	0.93 (0.003)		0.87 (0.008)	

$^{A,\ B}$ as defined above
Data provided as the average (standard deviation)

rent the dynamic sorption isotherms of each cycle in Fig. 5(a) and Fig. 5(b) behave like overlapped ellipses, which is similar to previous studies (Yang and Ma, 2013). Then the minimum sorption hysteresis ratio A/D, characterized by adsorption MC/desorption MC, for each cycle in the two conditions were calculated and listed in Table 4.

As shown in Table 4, the hysteresis ratio A/D for condition A is about 0.9, which is not far from the static range (Skaar, 1988), but higher than the value obtained for condition B, suggesting there is an shrinking effect by hydrothermal treatment on sorption hysteresis as well. However, both the A/D ratios are in positive relation with cyclic period while inversely with specimen thickness. This demonstrates that moisture sorption hysteresis decreased with cyclic period but increased with specimen thickness in this dynamic condition.

Further, slope for the long axis of the dynamic sorption isotherm as shown in Fig. 5 represents variation in MC per RH change, which is known as the moisture sorption coefficient (MSC) (Skaar, 1988), an parameter used to evaluate wood hygroscopicity. Fig. 6 shows the dynamic moisture sorption coefficient against different cyclic periods. It is evident that a positive relation exists between the moisture sorption coefficient and cyclic period at a given specimen thickness. For specimens cycled at the same period, the coefficient decreases with increasing specimen thickness, which is consistent with our previous study (Yang and Ma, 2015) where RH changed sinusoidally at a constant temperature. The intercepts of the Y-axis from the linear regression, corresponding to the values expected if the cyclic period is sufficiently long that moisture inside the specimens changes

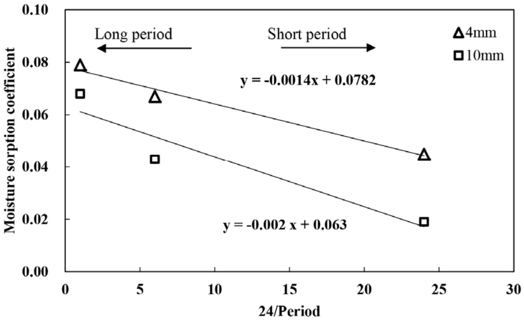


Fig. 6. Plots of dynamic moisture sorption coefficient at different cyclic periods for poplar wood under condition A.

Table 5. Comparison of MSC and HEC for poplar wood under different dynamic conditions

Thickness/mm	Period/h	MSC^A	MSC^B	HEC^A	HEC^B
4	1	0.045 (0.023)	0.040 (0.036)	0.019 (0.037)	0.014 (0.059)
	6	0.067 (0.014)	0.064 (0.027)	0.025 (0.023)	0.021 (0.037)
	24	0.079 (0.009)	0.076 (0.013)	0.032 (0.013)	0.027 (0.010)
10	1	0.019 (0.032)	0.013 (0.042)	0.009 (0.019)	0.009 (0.043)
	6	0.043 (0.021)	0.039 (0.012)	0.023 (0.017)	0.018 (0.028)
	24	0.068 (0.027)	0.064 (0.015)	0.027 (0.011)	0.023 (0.020)

$^{A, B}$ as defined above

Data provided as the average (standard deviation)

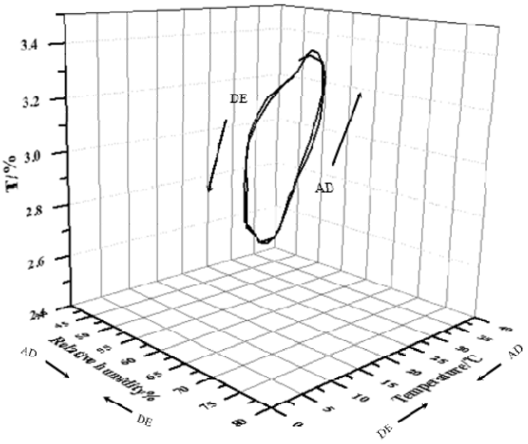


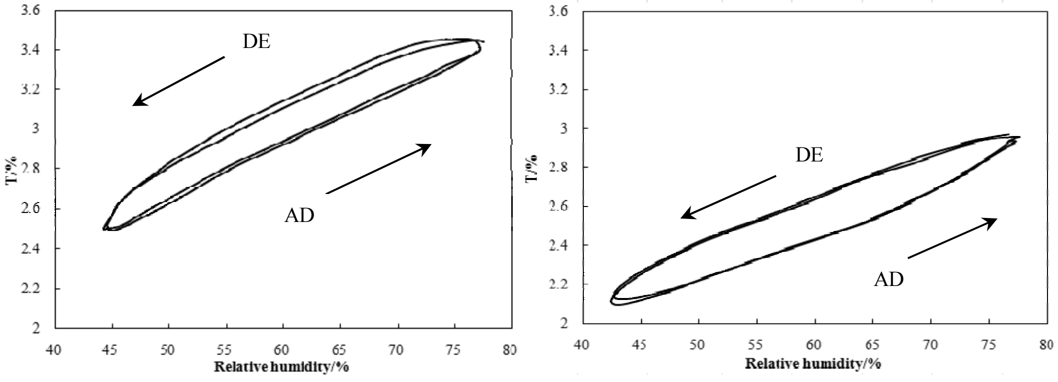
Fig. 7. Plots of dynamic T dimensional changes curves against temperature and RH for poplar wood under condition A (10 mm, 24 h) AD: adsorption DE: desorption.

uniformly without gradient, are 0.078 for 4 mm thick specimen and 0.063 for 10 mm thick specimen respectively, being much lower than the values from static condition (Noack *et al.*, 1973).

Comparison between MSC^A and MSC^B is further made in Table 5. It's obvious that the MSC^A is greater than MSC^B, this was as anticipated since the former moisture changes were caused by not only the RH but also the temperature changes.

Dynamic T dimensional changes of 10 mm thick poplar wood against temperature and RH cycled at 24 h is shown in Fig. 7 as an example for condition A, and Fig. 8(b) also offers the results for condition B as a control. Swelling hysteresis resulting from sorption hysteresis can be observed in a similar trend. To compare both conditions quantitatively, the projection of T-RH plane from the curve in Fig. 5 was drawn and presented in Fig. 8(a).

As the case of moisture sorption in Fig. 5, the slope for the long axis of the dynamic dimensional change curves as shown in Fig. 8 represents variation in wood dimension per RH change, known as the humidity expansion coefficient (HEC) (Skaar, 1988), an indicator used to assess wood dimensional stability. Comparison between HEC^A and HEC^B is also



(a) (b)

Fig. 8. Plots of T dimensional changes with RH for poplar wood under condition A (a) and condition B (b) (10 mm, 24 h).

conducted in Table 5. The similar tendency can be found between HEC and MSC that a positive relation could be found between the HEC and cyclic period at a given specimen thickness, and when specimens cycled at the same period, the coefficient decreases with increasing specimen thickness, which is also consistent with our previous study (Yang and Ma, 2015) where RH changed sinusoidally at a constant temperature. In addition, the HEC^A is greater than HEC^B, this could be also because the former dimensional change was caused by not only the RH but also the temperature variations.

4. CONCLUSION

Dynamic sorptive and hygroexpansive behaviors of wood in response to two cyclic hygrothermal effects where RH and temperature changed simultaneously in sinusoidal waves (condition A) and RH changed sinusoidally at constant temperature (condition B) were investigated, giving the following main conclusions:

1. Moisture and dimensional changes of the specimens were both generally sinusoidal in different dynamic conditions. Moisture increased with increasing cyclic period and decreased with specimen thickness, and it was less under condition B than condition A.
2. Both the moisture and dimensional amplitude increased with increasing cyclic period but all were lower for thicker specimens. The moisture and dimensional amplitude of condition A was larger than that of condition B for the combined effect of temperature and RH changes. The amplitude ratio of condition A to condition B ranged from 1.0 to 1.6 with the maximum value of 1.57 occurring at the shortest cyclic period in this study, not as much as expected.
3. Transverse anisotropy under different dynamic conditions was observed. T/R

increased as cyclic period increased or specimen thickness decreased. T/R of condition B was weaker than that of condition A.

4. Sorption hysteresis and swelling hysteresis existed, and sorption hysteresis was negatively related to cyclic period but in positive correlation with specimen thickness in these two dynamic conditions. Furthermore, sorption hysteresis of condition A was lower than that of condition B. Moisture sorption coefficient and humidity expansion coefficient increased with cyclic period and decreased with specimen thickness, and they both were higher in condition A.

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