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Dimensional Responses of Wood Under Cyclical Changing Temperature at Constant Relative Humidity[1]

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ABSTRACT

To investigate dimensional responses of wood under dynamic temperature condition, poplar (*populous euramericana* Cv.) specimens, 20 mm in radial (R) and tangential (T) directions with two thicknesses of 4 and 10 mm along the grain, were exposed to cyclic temperature changes in square wave between 25℃ and 40℃ at 60% relative humidity (RH) for three different cycling periods of 6 h, 12 h and 24 h. R and T dimensional changes measured during the cycling gave the following results: 1) Transverse dimensional changes of the specimens were generally square but at an opposite phase and lagged behind the imposed temperature changes. The phase lag was inversely correlated with cycling period, but positively related to specimen thickness, while the response amplitude was directly proportional to cycling period, but in a negative correlation with specimen thickness. 2) The specimens showed swelling hysteresis behavior. The heat shrinkage coefficient (HSC) became greater as cycling period increased or specimen thickness decreased. 3) Dimensional changes of the specimens produced deformation accumulation during repeated adsorption and desorption. The deformation accumulating ratio decreased with an increase in cycling period and specimen thickness. 4) Wood suffered 1.5 times as many dimensional changes per unit temperature variation as per unit humidity variation, and this deformation behaved even more seriously under static condition.

Keywords : cyclic temperature changes, dimensional responses, dynamic condition, wood

1. INTRODUCTION

Wood is a naturally hygroscopic material. Since daily temperature and humidity are hard to keep constant, moisture always moves in and out of wood cell wall, and dimensional changes in wood continually occur as a result (Ma and Zhao, 2012). Therefore, temperature, as an important factor (Unsal *et al.*, 2011), has received special attention in the research on hygroexpansive behavior of wood. Many studies showed that a decrease of approximately 1% of equilibrium moisture content could be observed for every increase of 10℃ between 20℃ and

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100℃ (Stamm and Loughborough, 1935; Kollmann, 1959; Weichert, 1963; Chang *et al*., 2012; Park *et al*., 2015). In addition, Mcmillen (1955) found that the shrinkage of Northern Red Oak increased when the drying temperature rose from 80℃ to 140℃. And Espenas (1971) also concluded that as temperature increased, T and R shrinkage of Douglas fir, Western Hemlock and Western Red Cedar became greater. Based on Mcmillen's study (Mcmillen, 1955), Espenas (1971) made a further investigation on how temperature affected wood hygroexpansion and related shrinkage (Park *et al*., 2015) to wood tension and compression strength which was a function of temperature as well.

However, these studies were mostly conducted under constant condition (static condition). Although static condition can simplify the research method, it is too ideal to provide scientific information for wood utilization. Therefore, dimensional changes of wood under dynamic condition aroused particular concern, which was first carried out by Stevens (1963) and termed "movement" to describe wood dimensional changes caused by changes in RH during atmospheric range. The study suggested that "movement" was considerably smaller than the dimensional changes of wood took place during initial drying from green condition, and it's a useful index for dimensional stability (Gong, 2001; Seung and Hee, 2015) of wood products in service. Chomcharn and Skaar (1983) then subjected wood specimens to sinusoidally varying RH between 77-47% at 25℃. Moisture and transverse dimensional changes were measured during the cyclic process. In our previous research, Ma *et al*. (2010) exposed Sitka spruce specimens at the size of 20 mm × 20 mm × 4 mm to sinusoidally RH between 45-75% at 20℃ for 1, 6, and 24 h, and measured moisture and R and T dimensional changes during the cycling.

Nevertheless, there are few studies available on hygroexpansion of wood under varying temperature condition up to the present. This work subjected wood specimens with two thicknesses to cyclic temperature changes in square wave between 25-40℃ at 60% RH, aiming at investigating dimensional responses of wood in dynamic temperature condition. The results from this study could be helpful in grasping the characteristics of wood at temperature non-equilibrium state and enriching wood physics theoretically, as well as improving wood processing and utilization through the regulation of dimensional stability practically.

2. MATERIALS and METHODS

Poplar (*populous euromericana* Cv.) was chosen as the study species. The specimens, 20 mm in R and T directions with two thicknesses of 4 mm and 10 mm along the grain, were initially oven-dried at 105℃. After their oven-dry dimensions in the three directions and weight were measured, they were conditioned at 60% RH controlled by saturated salt solution of sodium bromide (Macromolecule Academy, 1958) at 25 ± 0.2℃.

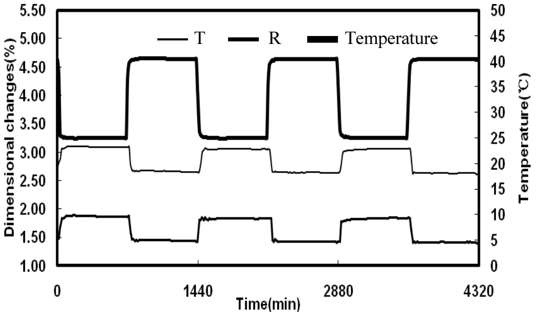

Fig. 1. Plots of temperature, T and R dimensional changes against cyclic time between 25-40℃ at 60% RH for 10 mm thick poplar wood (24 h).

They were then moved into a temperature conditioning chamber where RH was kept at 60% throughout the experiment and temperature changed in square wave between 25-40℃ for periods of 6 h, 12 h and 24 h. The temperature in the chamber was programmed to vary in discrete steps according to a predetermined schedule, and a thermo recorder was placed at the test specimens to ensure the desired conditions. R and T dimensional changes of the specimens in responses to the imposed temperature were recorded by three CCD laser displacement sensors (1 μm), while weight changes were measured by an electronic analytical balance (sensitivity ± 0.1 mg) (Ma *et al.*, 2010).

In addition, every group had three end-matched specimens for each cycle. The average values of the three tests for dimension of them were taken as the final result.

Table 1. Moisture content (MC) for poplar wood at 25℃ and 40℃ at 60% RH

Thickness (mm)	Period (h)	MC (%)	
		25℃	40℃
	6	10.13	9.71
4	12	10.79	10.23
	24	11.04	10.57
	6	9.72	9.41
10	12	10.31	9.84
	24	10.69	10.11

3. RESULTS and DISCUSSION

3.1. General dimensional responses

Dimensional responses of the specimens to temperature changes in square wave between 25-40℃ at 60% RH cycled at 24 h, as an example, is shown in Fig. 1 in which dimensional changes are given in terms of swelling based on oven-dry dimensions. It can be found that R and T dimensional changes were generally in square wave as well. An increase in temperature corresponds to decreased dimensions, leading to an opposite phase between temperature and dimensional changes of the specimens. This is as expected because moisture adsorbed by wood reduced as temperature increased (Cao *et al.*, 1997; Koji *et al.*, 2013; Murata *et al.*, 2013), which weakened the dimensional responses. Moreover, dimensional changes of the specimens lagged behind the impose temperature slightly.

Table 1 summarizes the moisture content (MC) for poplar wood at 25℃ and 40℃ under 60% RH. It's apparent that the MC increases

Table 2. Amplitude and phase lag of T and R dimensional response for poplar wood

Thickness (mm)	Period (h)	Amplitude (%) T	Amplitude (%) R	Phase lag (radians) T	Phase lag (radians) R
4	6	0.20	0.14	0.14	0.16
	12	0.27	0.18	0.13	0.15
	24	0.32	0.21	0.1	0.11
10	6	0.17	0.12	0.15	0.17
	12	0.21	0.15	0.15	0.16
	24	0.25	0.18	0.11	0.13

with the cyclic period and decreases with temperature and thickness. This is anticipated because specimens could have enough time to response to longer cyclic period, and higher temperature could reduce the sorption sites in wood (Engelund *et al.*, 2013), while there was not sufficient time for the thick specimens, especially their inner part, to respond to the temperature changes.

3.2. Amplitude and phase lag

The amplitude and phase lag of R and T dimensional changes are two parameters characterizing wood's ability to respond to varying environments, which both depend on the reaction time of the wood-water system. And the phase lag was described using the unit of radians calculated by the time difference between the peak value of R or T and changing temperature.

Table 2 lists the amplitude of R and T dimensional responses of different specimen thicknesses for each of the three cyclic periods. It is clear that as the cyclic period increases, the amplitude increases. This is anticipated because with longer cyclic period, the specimens could more sufficiently respond to the temperature changes. In addition, the amplitude decreases with the increasing thickness of specimens, since it is more difficult for the thicker specimens to react to temperature changes during the same time.

Table 2 also gives the phase lag of R and T dimensional responses of different specimen thicknesses at each of the three cyclic periods. There is a positive correlation between the phase lag and specimen thickness, namely, thicker specimens have greater phase lag values and response to temperature changes slowly. And tangential responses act faster than radial responses to dynamic condition, which may be attributed to the ray restraint effect (Gao *et al.*, 1995). On the other hand, the phase lag is inversely related to cyclic period due to the fact that their responses could more nearly follow the temperature changes with longer period.

3.3. Swelling hysteresis

The first cycle of T dimensional changes against cyclic temperature for 10 mm thick specimens cycled at 12 h is shown in Fig. 2 as an example. Swelling hysteresis, namely the original shrinkage is never fully reversed with re-adsorption after original drying, caused by sorption hysteresis (Ma and Zhao, 2012) can be clearly observed in the figure.

The slope of the lines in this figure represents variation in wood dimensional change per

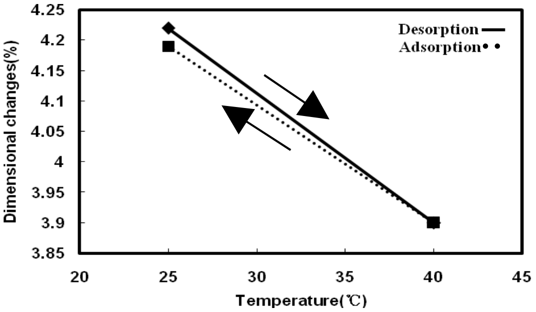

Fig. 2. The first cyclic tangential dimensional change of 10 mm thick poplar wood against cyclic temperature (12 h).

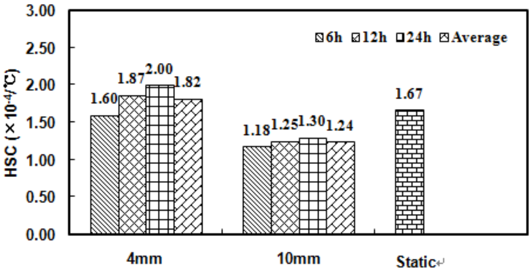

Fig. 3. Plots of the HSC of poplar under dynamic condition.

temperature change, which is defined as heat shrinkage coefficient (HSC) here, an index to reflect dimensional instability of wood by moisture exchange due to atmospheric temperature varying. Fig. 3 summarizes the dynamic HSC of the specimens for different cycle periods, which is in the same range with static result from Western Hemlock (Espenas, 1971). It indicates that the HSC value is proportional to cyclic period, but in negative correlation with specimen thickness.

As shown in Fig. 3, the HSC value of wood is at the order of magnitude of 10^{-4}/℃, which is significantly different from the thermal expansion coefficient (TEC) resulted directly from temperature increase. Generally, TEC is at the order of magnitude of 10^{-6}-10^{-5}/℃ (Gao *et al*., 1995; Liu and Zhao, 2004; Walter and Peter, 2006), much lower than the HSC. This implies that dimensional responses owing to water evaporation during heating were more notable than those coming from thermal expansion, because the loss of sorption sites caused by heating could lead to a decrease in MC as shown in Table 1, and as a result, the dimension of wood decreased indirectly, which was also the case in previous study (Xu, 2006; Engelund *et al*., 2013; Yang and Ma, 2015). Therefore, the dimensional changes due to thermal expansion could be negligible in this work.

3.4. Deformation accumulation

Fig. 4 presents the deformation accumulation of 4 mm thick specimens by cyclic temperature effect. It is evident that tangential dimension continuously decreases with the increasing number of cycles, meaning that the deformation can be accumulated (Zhang *et al*., 2006).

The mean value for the first peak of the square wave was taken as a base, on which dimensional change ratio in the following cycles was calculated and termed as deformation accumulation ratio (DAR) in this study. Its relation with cycle number is illustrated in Fig. 5.

For specimens at different thicknesses, deformation accumulates gradually with increasing cycle number, approaching an “equilibrium”

Table 3. Tangential and radial deformation accumulating ratio under different experimental conditions

Thickness (mm)	Period (h)	DAR (%)	
		T	R
4	6	0.195	0.062
	12	0.143	0.058
	24	0.074	0.030
10	6	0.118	0.045
	12	0.084	0.034
	24	0.070	0.030

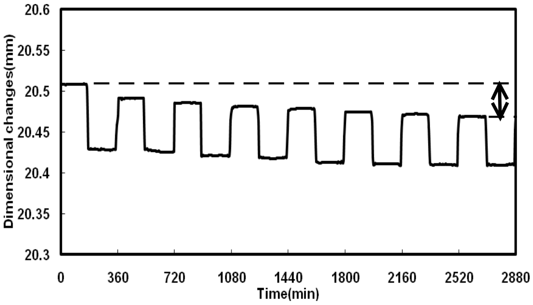

Fig. 4. Dimensional change of 4 mm thick wood under dynamic condition (6 h, Tangential).

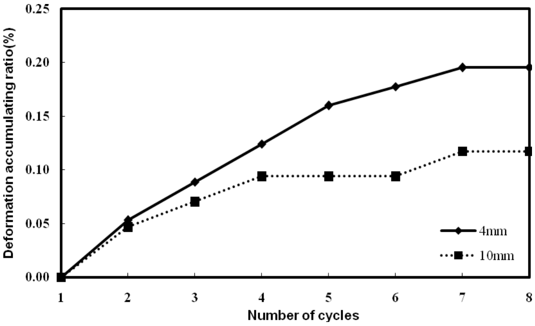

Fig. 5. Deformation accumulating ratio of 4 mm thick wood against number of cycles (6 h, Tangential).

state slowly. At about 7th or 8th cycle, when hygroexpansion of the specimens still takes place by temperature changes without any further accumulation of deformation, it seems as if a "set" state is reached (Wang and Zhao, 1999).

Table 3 gives the DAR of the specimens for the three cyclic periods. It demonstrates that the ratio decreases as cyclic period increases. At a given cyclic period, deformation accumulating for 4 mm thick specimens is more remarkable than that for 10 mm. This is consistent with the amplitude data discussed in Table 2. That is, the amplitude response to temperature changes of 10 mm thick specimens is weaker than that of 4 mm thickness, causing that deformation accumulation for thick specimens is lower. Furthermore, there are differences in R and T deformation accumulation as well. DAR is lower in R direction than T direction, which probably results from the restraint effect by horizontally oriented wood ray. In detail, T DAR is twice as much as R DAR and the ratio of them decreases with increasing cyclic periods, stating the transverse anisotropy in deformation accumulation.

3.5. Comparation of wood dimensional response to temperature and humidity under dynamic condition

Rasmussen (1961) measured the EMC of

Table 4. Expansion (shrinkage) coefficients of wood under static condition (25-40℃, 60% RH) and dynamic condition changed sinusoidally between 45 and 75% at 25℃ and 40℃

Thickness (mm)	Period (h)	Expansion (shrinkage) coefficients (/℃)	
		Temperature changes	Humidity changes (Yang and Ma, 2013)
4	6	1.60×10^{-4}	2.50×10^{-4}
	24	2.00×10^{-4}	3.00×10^{-4}
10	6	1.18×10^{-4}	1.80×10^{-4}
	24	1.30×10^{-4}	2.30×10^{-4}

Picea sitchensis Carr, and from the adsorption isotherms obtained, it can be found that the humidity expansion coefficient is two to three times of heat shrinkage coefficient in static condition.

Table 4 compares the expansion (shrinkage) coefficients of wood under different dynamic conditions. Wood suffers 1.5 times as many dimensional changes per unit temperature variation as per unit humidity variation presented in our previous study (Yang and Ma, 2013), where specimens of the same species and sizes were used but relative humidity changed cyclically. Therefore, it is apparent that differences exist between the effect of temperature and humidity changes on wood deformation and the static impact is much more serious than the dynamic condition.

4. CONCLUSION

Dimensional responses of wood subjected to cyclical temperature changes were investigated in this study, giving the following results:

1) Transverse dimensional changes of the specimens were generally square but at an opposite phase and lagged behind the imposed temperature changes. The phase lag was inversely correlated with cycling period, but positively related to specimen thickness, while the response amplitude was directly proportional to cycling period, but in a negative correlation with specimen thickness.
2) The specimens showed swelling hysteresis behavior. The HSC became greater as cycling period increased or specimen thickness decreased.
3) Dimensional changes of the specimens produced deformation accumulation during repeated adsorption and desorption. The deformation accumulating ratio decreased with an increase in cycling period and specimen thickness.
4) Wood suffered 1.5 times as many dimensional changes per unit temperature variation as per unit humidity variation, and this deformation behaved even more seriously under static condition.

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