

Hygroscopic Properties of Six Tree Species with Four Tangential Thicknesses

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The differences of hygroscopic property among six tree species with four thicknesses were examined. The density, chemical composition, crystallinity, equilibrium moisture content (EMC), and moisture absorption rate were measured by static saturated salt solution method, and the isothermal moisture absorption curve was fitted by the H-H model to analyze monolayer molecular adsorption and multilayer molecular adsorption. The results show that under the same relative humidity (RH), the EMC of *Picea asperata* and *Populus deltoides* were increased with increasing thickness, while that of *Quercus* spp. and *Xanthostemon melanoxylon* were decreased. The moisture absorption rate of *P. asperata* was the largest and that of *X. melanoxylon* was the smallest. When RH ranged from 0 to 97%, the monolayer molecular adsorption water amount of samples with different thicknesses of the six tree species gradually became close. With the increase of tree species density, the monolayer molecular adsorption water amount of the thinner sample is gradually greater than that of the thicker sample. The change of multi-layer molecular adsorption water content is consistent with that of EMC, Moisture absorption rate, monolayer molecular adsorption water, and multilayer molecular adsorption water are related to the chemical composition content, density, and thickness of tree species.

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INTRODUCTION

Wood is a renewable material that is widely used in construction engineering, furniture manufacturing, and interior decoration. Due to its hygroscopic properties, it often leads to quality problems such as cracking and deformation during the process of production, processing, or use. Due to the different thickness of tree species and wood used in furniture products and interior decoration materials, the quality problems are also different. For instance, thick parts in solid wood furniture rarely have problems, while thin parts with the same tree species and moisture content are prone to cracking, joint pulling, and other problems. The problems caused by the hygroscopicity of wood of different tree species and different thicknesses have been studied (Neimsuwan *et al.* 2008; Fernandez *et al.* 2014; Podlena *et al.* 2017; Murr and Lackner 2018; Kalita *et al.* 2019). There has been research on the effects of different tree species and samples of different specifications (Skaar 1988; Ma *et al.* 2010; Fernandez *et al.* 2014; Yang *et al.* 2018; Majka *et al.* 2019; Mvondo *et al.* 2021). In addition, effects of wood chemical composition (Rowell 2005) on wood moisture absorption, and the correlation between wood moisture absorption and

wood species, wood thickness, and wood chemical composition content have been investigated. Although the hygroscopicity of a variety of tree species and wood thickness has been studied, there are few systematic comparative studies on the hygroscopic differences between coniferous wood and broad-leaved wood, and the hygroscopic differences between the same tree species and wood thickness.

Wood is a renewable material widely used in construction, furniture manufacturing, and interior decoration. Due to its hygroscopic properties, when the ambient temperature and humidity change, it will absorb or release moisture, leading to swelling or shrinkage, resulting in quality problems such as cracking and deformation during production, processing, or use. Due to the different tree species and wood thicknesses used in furniture products and upholstery materials, there are also differences in the quality problems that arise. For example, thick parts in solid wood furniture rarely have problems, while thin plate parts of the same tree species and moisture content are prone to cracking, pulling, and other problems. Therefore, the problems caused by the hygroscopicity of wood of different tree species and different thicknesses have attracted the attention of some scholars (Neimsuwan *et al.* 2008; Podlena *et al.* 2017; Murr and Lackner 2018).

Scholars have carried out a large number of experiments to test the effects of different tree species, samples of different specifications (Mvondo *et al.* 1988; Ma *et al.* 2010; Yang *et al.* 2018; Majka *et al.* 2019), and wood chemical composition (Rowell 2005) on the hygroscopicity of wood. The difference in wood moisture absorption of different tree species is related to the content of internal chemical components and crystallinity (Huang and Wang 2014). Fernandez *et al.* (2014) used the saturated salt solution method to study the difference in adsorption of the two tree species at different temperatures. They analyzed the reasons for the difference in combination with softwood, hardwood, functional groups, and crystallinity. It was found that the hemicellulose content of the hardwood was higher than that of the softwood, and the crystallinity was lower, the adsorption sites were more, and the hygroscopic equilibrium moisture content that could be achieved was higher.

Murr and Lackner (2018) studied the adsorption kinetics of wood with different particle sizes and thicknesses. They found that the smaller the particle size and the smaller the thickness of the sample, the faster the mass increase of the sample, and the faster the time for the sample with smaller thickness to reach equilibrium for thicker samples. Yang and Ma (2013) studied the change of water content of different tree species and samples of different sizes under the condition of cyclic change of relative humidity and found that the samples with larger thickness achieved lower water content when using the same time and temperature and humidity conditions. The magnitude of radial and chordwise dimension changes is small, and the chordwise change is always greater than the radial dimension. This is because wood is an anisotropic material with different shrinkage and expansion in different directions.

The largest dimensional change occurs in the direction tangent to the growth rings, and the shrinkage is smaller along the wood ray direction. Shrinkage is minimal in the longitudinal direction (Kalita *et al.* 2019). Many scholars have studied the relationship between the hygroscopicity of wood and wood species, wood thickness, and wood chemical composition content. However, there are few systematic comparative studies on the hygroscopic difference between softwood and hardwood, and the difference in hygroscopicity between woods of the same species but different thicknesses.

This study determined the differences of equilibrium moisture content (EMC) and moisture absorption rate of six kinds of tree species with four thicknesses of wood by the

static saturated salt solution adsorption method. The Hailwood Horrobin (H-H) model was used to fit the isothermal moisture absorption curve of wood, analyze the monolayer molecular adsorption and multi-layer molecular adsorption, and explore the reasons for the differences in moisture absorption of different tree species with different thickness of wood. This data will provide solutions to the quality problems of furniture products and interior decoration materials in production and use.

EXPERIMENTAL

Test Materials

Populus deltoides was provided by Jiangsu Siyang Meizhi Wood Industry Co., Ltd. (Siyang, China); *Picea asperata*, *Carpinus* L., *Quercus* spp., and *Zelkova schneideriana* were provided by Ningbo Senhe musical instrument Co., Ltd. (Ningbo, China). *Xanthostemon melanoxylon* was provided by Zhejiang Huzhou Lezai Wood Industry Co., Ltd. (Huzhou, China).

Sample preparation: The sample is heartwood, the specifications were 20 mm (*L*) × 20 mm (*R*) × 1 mm (*T*), 20 mm (*L*) × 20 mm (*R*) × 4 mm (*T*), 20 mm (*L*) × 20 mm (*R*) × 8 mm (*T*), 20 mm (*L*) × 20 mm (*R*) × 20 mm (*T*). Initial moisture content: *Carpinus* L. 10.53%, *Picea asperata* 10.49%, *Quercus* spp. 12.49%, *Populus deltoides* 12.77%, *Zelkova schneideriana* 12.45%, *Xanthostemon melanoxylon* 9.79%.

The wood of six tree species was sawn into 20 mm × 20 mm × 1 mm (*T*), 20 mm × 20 mm × 4 mm (*T*), 20 mm × 20 mm × 8 mm (*T*), and 20 mm × 20 mm × 20 mm (*T*) samples. The thickness was in the tangential direction, and there were five static saturated salt solution moisture absorption test samples conducted for each tree species and thickness.

Determination of Wood Density and Chemical Composition Content

The measured density is the full dry density and the method for determining the density of wood was in accordance with the standard Method for determination of the density of wood (GB/T 1933-2009 Method for determination of the density of wood). The contents of benzene alcohol extract, acid insoluble lignin, holocellulose, and pentose in wood were determined as described (Luostarinen and Hakkarainen 2019; Domingos *et al.* 2020).

Determination of Crystallinity

The crystallinity of absolute dry wood powder passing through a 100-mesh sieve was determined. The combined multi-functional horizontal X-ray diffractometer (XRD; Ultima IV, Nippon Science Company, Japan) was used with the following parameters: wavelength input 0.154058 nm, slit device $D_s=1^\circ$, $S_s=1^\circ$, $R_s=0.3\text{mm}$, voltage 40 kV, current 30 mA, scanning angle 4 to 50° , sampling spacing 0.1° , and scanning speed $5^\circ/\text{min}$.

Static Saturated Salt Solution Humidity Absorption Test

The dryer was placed in a constant temperature and humidity box with a set temperature of 30°C . The saturated salt solution inside the dryer stabilizes the relative humidity (RH) (Li *et al.* 2016). The saturated salt solution is shown in Table 1.

Table 1. Relative Humidity Corresponding to 30 °C Saturated Salt Solution

Salt	Magnesium Chloride	Sodium Bromide	Sodium Chloride	Potassium Sulphate
RH (%)	32.44 ± 0.14	56.03 ± 0.38	75.09 ± 0.11	97 ± 0.4

The moisture absorption test of the sample consists of four stages: stage A: 0% to 32% RH; Stage B: 32% to 56% RH; Stage C: 56% to 75% RH; Stage D: 75% to 97% RH. The sample was dried to absolute dryness, weighed (M_0), and then subjected to isothermal adsorption test phase A. During the moisture absorption process, the sample was weighed again in different time periods and recorded as M_i . The measurement time i was 2, 4, 6, 18, 30, 42, 54, 66, and 78 h after the sample is put into the dryer. The sample mass was measured every 48 h until moisture absorption equilibrium was reached. After the sample reached the isothermal moisture absorption equilibrium in each stage, the saturated salt solution was replaced for the moisture absorption test in the next stage.

The moisture content was calculated by Eq. 1,

$$MC_i = (M_i - M_0)/M_0 \times 100\% \quad (1)$$

where MC_i is the moisture content of wood at moisture absorption i time, M_i is the mass of wood sample with moisture absorption i time, and M_0 is the absolute dry mass of hygroscopic sample.

The moisture absorption rate is the change of hourly moisture content of the sample per unit of time, based on two adjacent measurements, calculated as follows,

$$V_{i_1 \sim i_2} = \frac{M_{i_2} - M_{i_1}}{i_2 - i_1} \quad (2)$$

where $V_{i_1 \sim i_2}$ is the average hourly moisture absorption rate in the i_1 to i_2 time period, M_{i_1} , M_{i_2} is the moisture content of sample at measuring time i_1 , i_2 , and i_1 and i_2 are adjacent time points for sample quality measurement.

H-H Model Isothermal Adsorption Curve Fitting

The H-H model was used analyze the isothermal adsorption of wood moisture (Hailwood and Horrobin 1946); it can predict the change of monolayer molecular adsorption moisture content in a wide RH range, which is in line with the characteristics of wood dry shrinkage and wet expansion (Hill *et al.* 2010).

The EMC of wood in different RH environments can be expressed as follows,

$$M = M_h + M_d = \frac{18}{W} \left(\frac{K_1 K_2 H}{1 + K_1 K_2 H} + \frac{K_2 H}{1 - K_2 H} \right) \quad (3)$$

where M is the equilibrium moisture content of the sample, M_h is the amount of water adsorbed by monolayer molecules, M_d is the amount of water adsorbed by multilayer molecules, W is the mass of absolutely dry wood containing adsorption sites per mole ($\text{g} \cdot \text{mol}^{-1}$), H is relative humidity, K_1 is the equilibrium constant between monolayer molecular adsorbed water and multilayer molecular adsorbed water, and K_2 is the equilibrium constant between water adsorbed by multilayer molecules and environment temperature and humidity.

Equation 3 can be sorted into the following polynomial form,

$$\frac{H}{M} = A + BH - CH^2 \quad (4)$$

where A , B , and C are polynomial fitting parameters. The relationship between fitting parameters and W , K_1 , and K_2 is shown below.

$$A = \frac{W}{18} \times \frac{1}{K_2(K_1+1)} \quad (5)$$

$$B = \frac{W}{18} \times \frac{K_1-1}{K_1+1} \quad (6)$$

$$C = \frac{W}{18} \times \frac{K_1K_2}{K_2+1} \quad (7)$$

In this study, Origin 2021 software (Origin Lab, America) was used to fit the water isothermal adsorption curve.

RESULTS AND DISCUSSION

Wood Density, Chemical Composition Content, and Crystallinity

The density values of six kinds of wood were determined as follows: *Picea asperata*, 0.36 g/cm³; *Populus deltoides*, 0.44 g/cm³; *Zelkova schneideriana*, 0.67 g/cm³; *Carpinus* L, 0.71 g/cm³; *Quercus* spp., 0.75 g/cm³; and *Xanthostemon melanoxylon*, 1.23 g/cm³.

Table 2 shows the average value of chemical composition of six tree species. The content of holocellulose of *X. melanoxylon*, *P. asperata*, *Z. schneideriana*, *Carpinus* L, *Quercus* spp. and *P. deltoides* decreased successively. The content of benzene alcohol extract of *X. melanoxylon* was higher, and the content of benzene alcohol extract of *Z. schneideriana* was the lowest.

Table 2. Average Content of Chemical Components of 6 Tree Species

Tree species	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Alcohol Benzene Extractive (%)
<i>Picea asperata</i>	49.43	19.15	20.60	1.87
<i>Populus deltoides</i>	36.38	12.73	43.70	1.93
<i>Zelkova schneideriana</i>	44.73	23.07	27.12	0.81
<i>Carpinus</i> L	47.60	17.68	26.94	1.71
<i>Quercus</i> spp.	40.41	22.64	23.27	2.83
<i>Xanthostemon melanoxylon</i>	45.72	23.14	21.98	5.12

Figure 1 shows the diffraction intensity curves of six tree species by X-ray diffraction. The crystallinity of six tree species was obtained as follows: *Z. schneideriana*, 41.65%; *Quercus* spp., 42.26%; *P. asperata*, 42.35%; *P. deltoides*, 43.39%; *Carpinus* L, 45.38%; and *X. melanoxylon*, 49.32%.

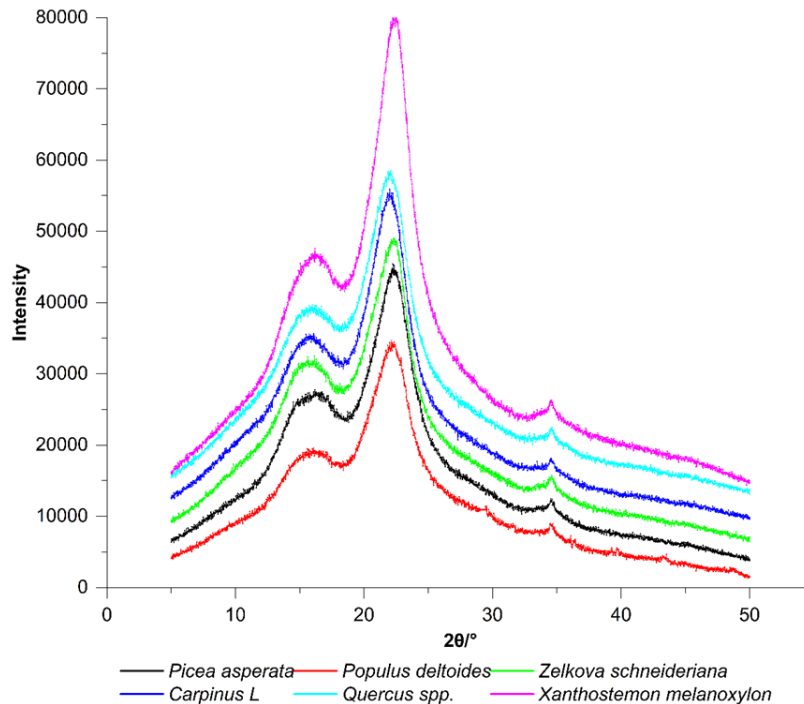


Fig. 1. Diffraction intensity curve of wood X-ray diffraction method

Equilibrium Moisture Content and Moisture Absorption Rate of Wood

Balanced moisture content of wood

Figure 2 shows the relationship between mean moisture absorption EMC and thickness of six tree species in four stages. In stages A, B, and C, the EMC of *P. asperata* and *P. deltoides* increased with the increase of sample thickness. The reason may be that *P. asperata* and *P. deltoides* have low density and high porosity (Plotze and Niemz 2011), and water molecules more easily enter the interior of wood and combine with free hydroxyl groups (Jang *et al.* 2020). During moisture absorption, hydrogen bonds within the polysaccharide structure break, and volume expansion creates cracks between wood microfibrils (Hartley *et al.* 1992). More adsorption sites are produced, which increases the wood EMC. The EMC of *Z. schneideriana* and *Carpinus L* had little correlation with the change of sample thickness. The EMC of thin samples of *Quercus spp.* and *X. melanoxylon* was higher than that of thick samples. The reason is that the density of *Z. schneideriana* and *Carpinus L* species is large. The structure is relatively compact, and the total porosity is about 60% of *P. asperata* (Plotze and Niemz 2011). When the sample thickness increases, it is relatively difficult for water to enter the wood. A number of hydrogen bonds break, and the extent of volume expansion decreases, resulting in small changes in EMC of samples with different thickness. *Quercus spp.* and *X. melanoxylon* have higher wood density, high extractives content, and compact structure. When the sample thickness increases, it is difficult for water to enter the wood, with less hydrogen bond fracture and volumetric expansion produces fewer cracks (Mantanis *et al.* 1994; Morisato *et al.* 2002), resulting in reduced EMC.

The increase of EMC in phase D of the moisture absorption test was much greater than that in phases A, B, and C. The possible explanation is the adsorption of free water in the capillary (Hill 2006). The other explanation is related to the glass transition of hemicellulose (Vrentas and Vrentas 1991; Thygesen *et al.* 2010) and the water molecular

monomer first binds to the adsorption site at low RH, converted to dimer at high RH (Willems 2018).

Figure 3 shows the relationship between EMC mean value of four kinds of wood thickness and tree species. In stages A, B and C, the EMC of *P. asperata* was always higher than that of other tree species, which may be due to the high content of holocellulose and low crystallinity of *P. asperata*, making the moisture absorption of *P. asperata* larger. The average EMC of *P. deltoides* was the lowest, which was related to the lowest content of cellulose and hemicellulose. With the increase of RH, the EMC of *Quercus* spp. and *X. melanoxylon* gradually became smaller than that of *Z. schneideriana* and *Carpinus* L, which may be due to the high density and extract content, resulting in low expansion rate and reduced multi-layer molecular adsorption (Morisato *et al.* 2002). The EMC of *Carpinus* L was always lower than that of *Z. schneideriana* because the content of *Z. schneideriana* holocellulose was high and the crystallinity was lower than that of *Carpinus* L. In phase D, the EMC of the four kinds of wood decreased with the increase of tree species density, which may be due to the minimum density of *Z. schneideriana* and the high content of holocellulose. In addition, the wood density and extract content limited the amount of water adsorbed by multi-layer molecules.

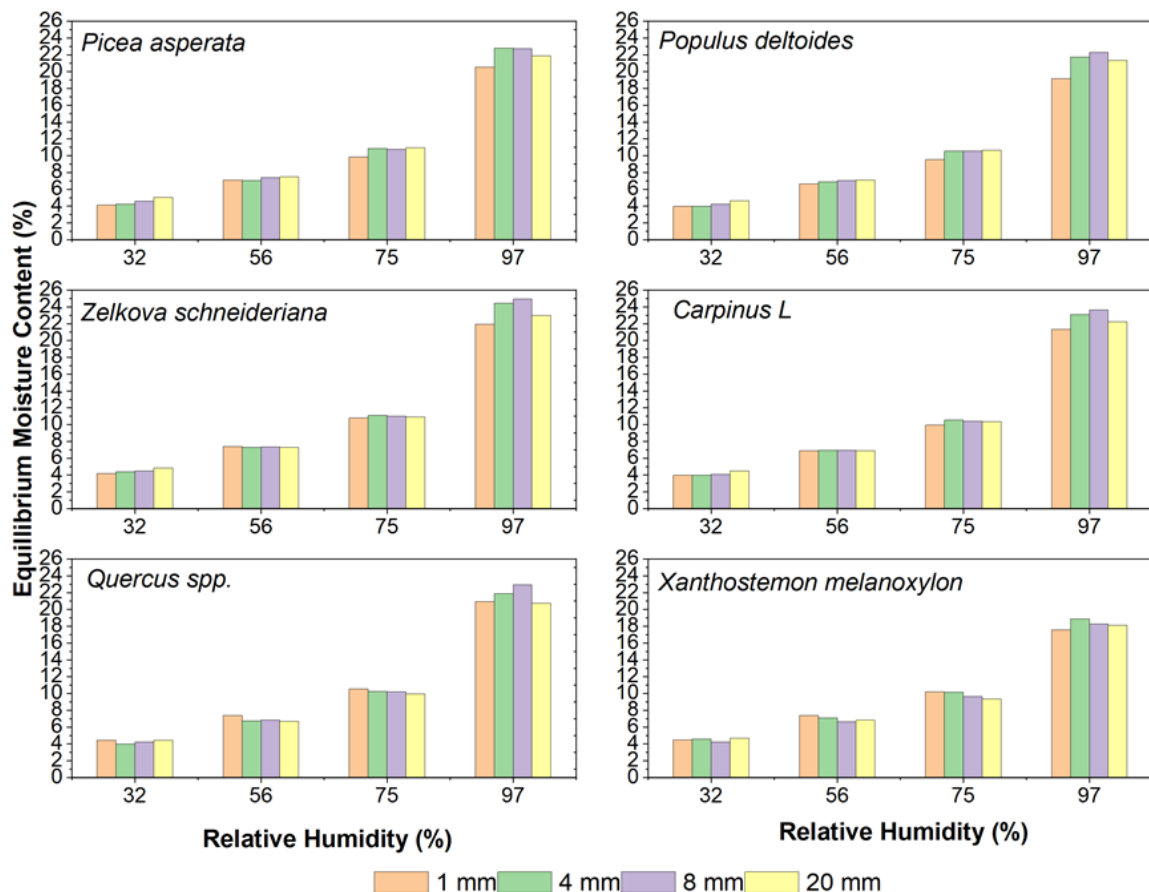


Fig. 2. Equilibrium moisture content of six tree species wood with four thicknesses

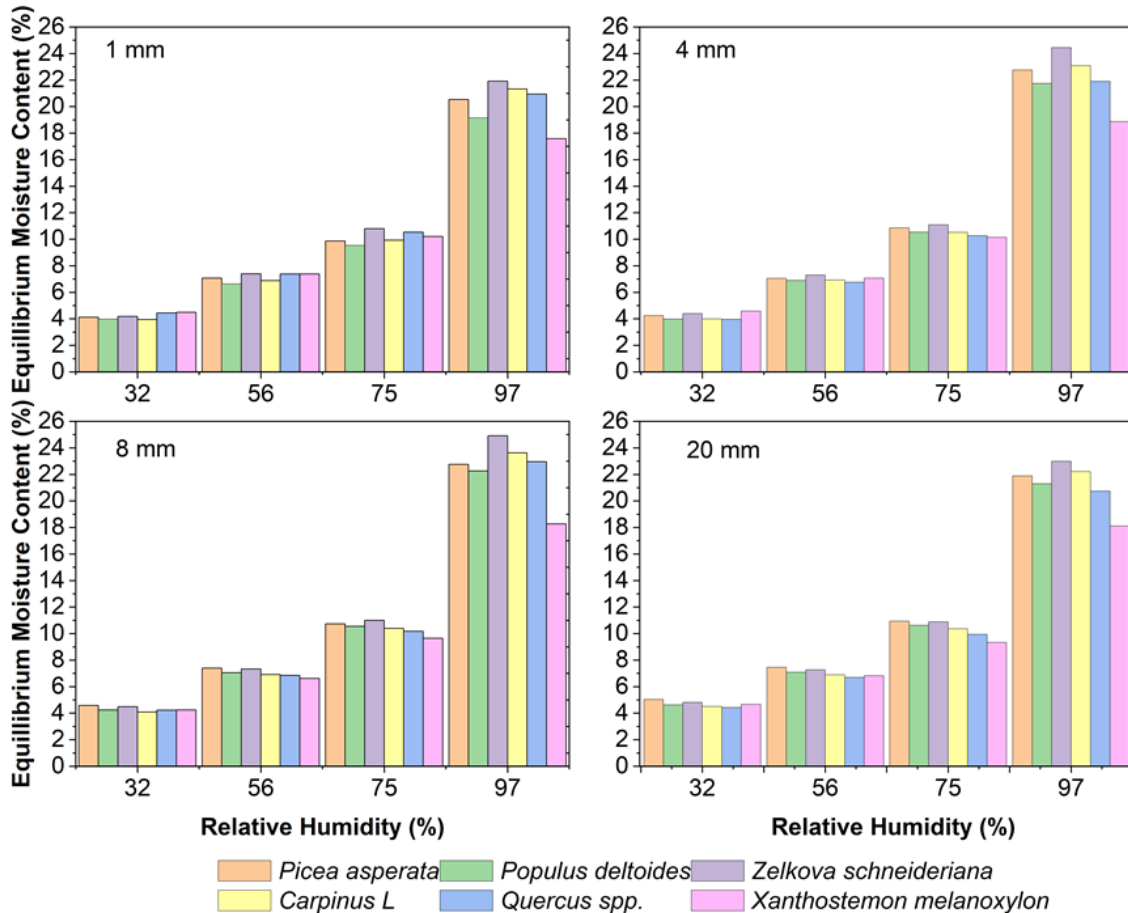


Fig. 3. Equilibrium moisture content of six tree species wood with four thicknesses (4 sample thicknesses of 1mm-20 mm)

Differences of moisture absorption rate of wood

Figures 4 through 7 show the relationship between moisture absorption rate and moisture absorption time of samples of six tree species and four thicknesses in stages, A, B, C, and D (take 4 mm, 20 mm thick sample and *P. asperata*, *Quercus* spp. as examples). At the beginning of each stage, the sample was put into the dryer.

The partial pressure of water vapor in the dryer was higher than that on the wood surface. When the wood absorbs water vapor quickly, the moisture absorption rate is large, and the moisture content increases rapidly. With the progress of moisture absorption process, the water vapor differential pressure decreases, and the moisture absorption rate of wood gradually decreases to zero.

The time required for each sample in the figure to reach EMC ranged from 78 h to 1,326 h. When the moisture absorption time was longer than 78 h, the moisture absorption rate was less than 0.05% per h, which was difficult to distinguish, so only the moisture absorption rate in the first 78 h was analyzed.

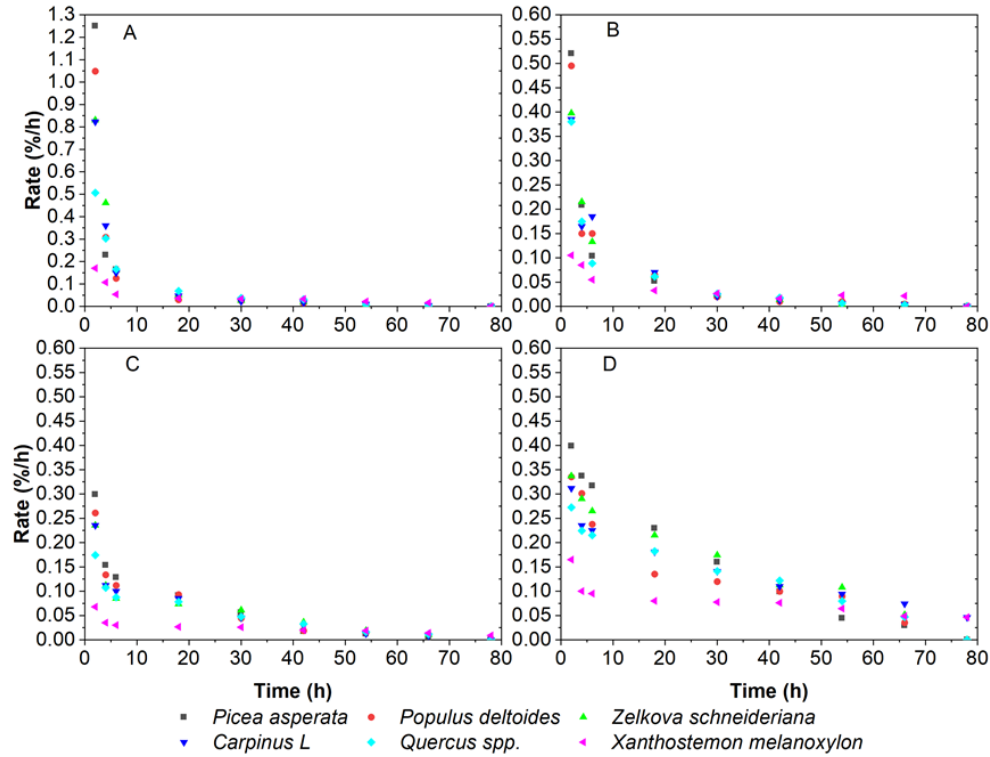


Fig. 4. Relationship between moisture absorption rate and moisture absorption time of wood with 4 mm thickness (A, B, C, D are four stages of moisture absorption test: A: 0%-32%RH; B: 32%-56%RH; C: 56%-75%RH; D: 75%- 97%RH)

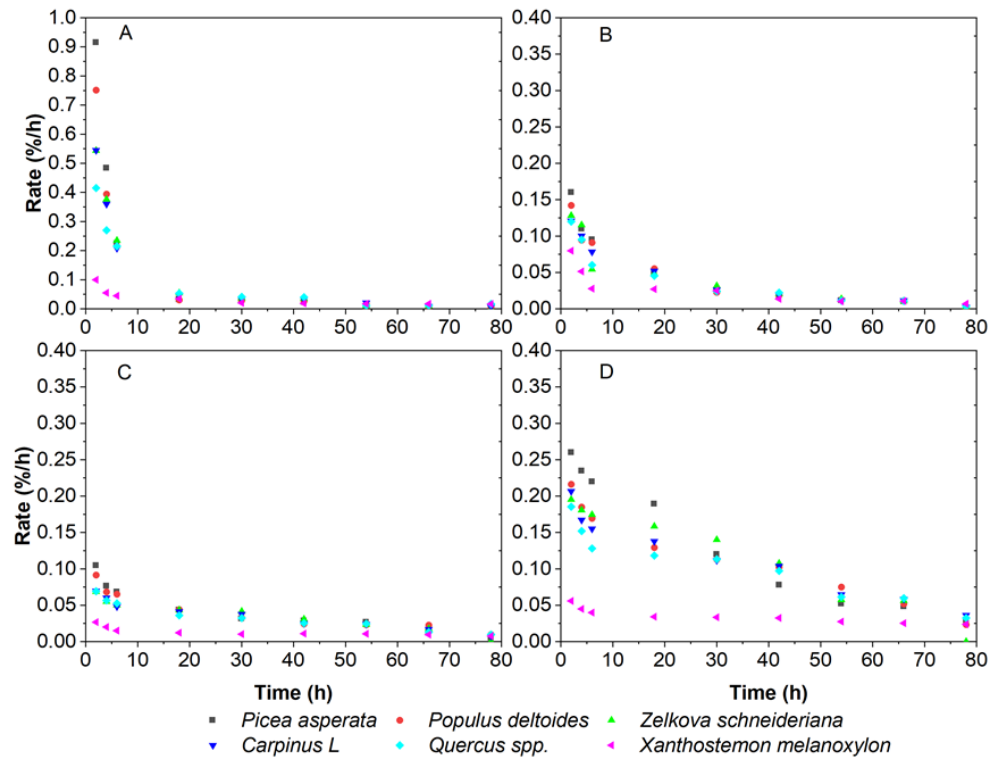


Fig. 5. Relationship between moisture absorption rate and moisture absorption time of wood 20 mm thickness (A, B, C, D are four stages of moisture absorption test: A: 0%-32%RH; B: 32%-56%RH; C: 56%-75%RH; D: 75%- 97%RH)

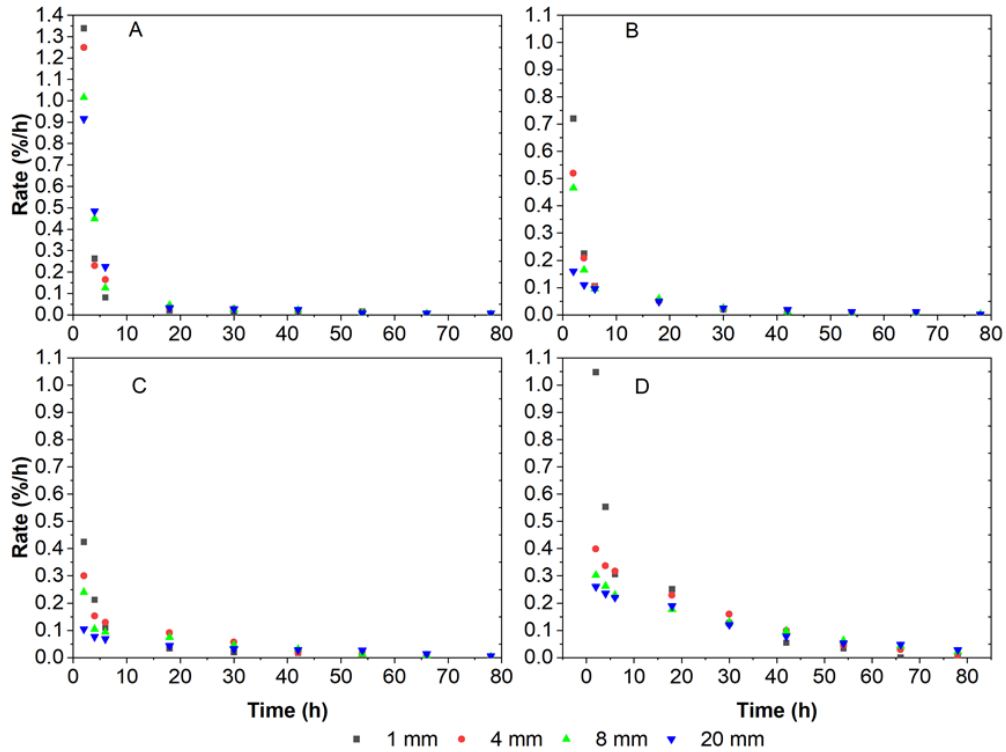


Fig. 6. Relationship between hygroscopic velocity and hygroscopic time of *P. asperata* with four thicknesses

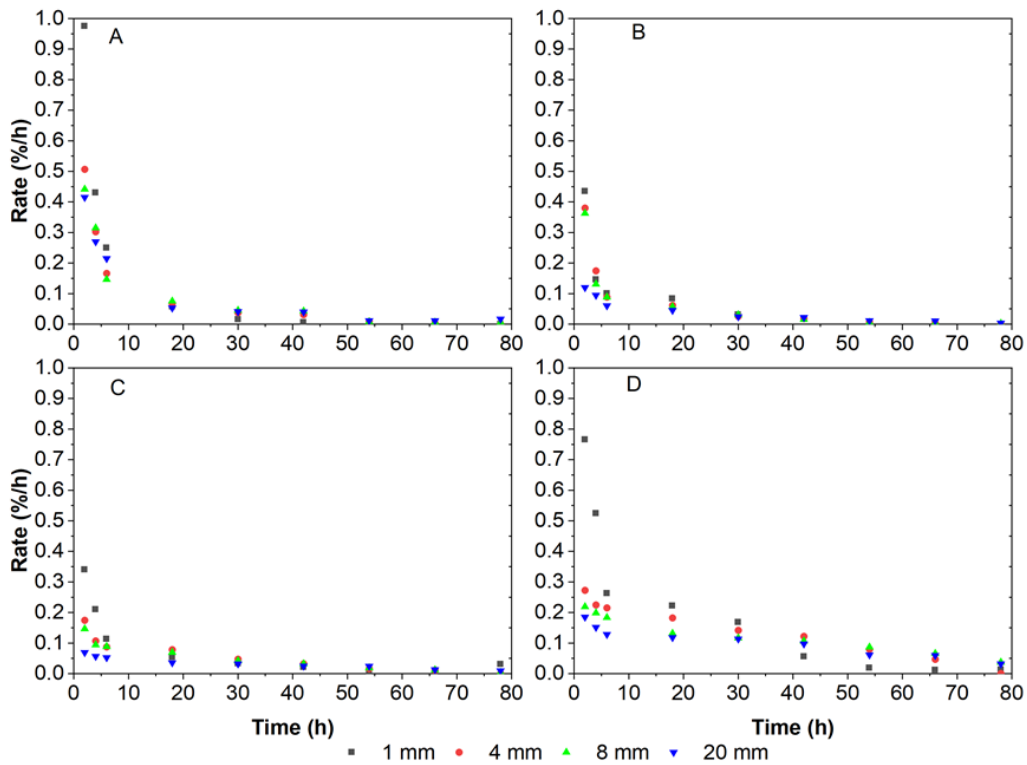


Fig. 7. Relationship between hygroscopic velocity and hygroscopic time of *Quercus* spp. with four thicknesses

At the beginning of the moisture absorption test in Figs. 4 and 5, the moisture absorption rate of *P. asperata* was the largest. It may be that the axial tracheids of coniferous *P. asperata* are larger in diameter than those of other five broad-leaved wood fiber cells, and there are many pits on the cell wall with large pore diameter. Water can enter the wood faster, so the water movement speed is faster than that of broad-leaved wood. The moisture absorption rate of *P. deltooides* was slightly higher than that of *Z. schneideriana*, *Carpinus* L and *Quercus* spp., which may be caused by the joint influence of two aspects. The density of *P. deltooides* is slightly higher than that of *P. asperata* and lower than that of the other four tree species. The higher density of broad-leaved wood results in more wood fiber content; the thicker cell wall of wood fiber means there are smaller cell cavities. However, the lignin content and crystallinity of *P. deltooides* are high, and the content of holocellulose is the lowest, resulting in less free hydroxyl content in *P. deltooides* wood. Among other broad-leaved trees, the initial moisture absorption rate of *Z. schneideriana* and *Carpinus* L was similar and greater than that of *Quercus* spp., which may be due to the fact that *Quercus* spp. has more inclusions, which affect the pore circulation of cell wall, block the grain pores, and affect the transmission of water, resulting in a small moisture absorption rate. The lowest moisture absorption rate of *X. melanoxylon* in the initial stage is because it has the highest density, crystallinity, and benzene alcohol extract contents, and it has the longest time to achieve absorption stability. When the moisture absorption rate of the other five species gradually decreased to zero, *X. melanoxylon* did not reach the moisture absorption balance. Figures 6 and 7 show that the moisture absorption rate decreased with the increase of sample thickness because the difficulty of water entering the wood increases with the increase of sample thickness.

In Figs. 4 to 7, there are differences in the time required for the samples in stages A, B, C, and D to reach EMC. The time required for the continued moisture absorption to approach zero increased with increasing RH, which may be because the higher RH is associated with the higher EMC of wood. With the increase of sample thickness, the moisture absorption extent of wood decreased as a whole. The time required for moisture absorption to reach EMC was prolonged because the increase of sample thickness requires more pores for moisture diffusion into the wood, resulting in the decrease of velocity.

There were differences in the time for wood samples of different tree species and different thicknesses to reach EMC. The greater density between different tree species and the greater thickness of the sample of the same tree species resulted in a longer time required to reach the moisture absorption equilibrium. This is due to the different moisture absorption rate, which is also one of the indicators to measure the moisture absorption.

H-H Model Isothermal Moisture Absorption Curve Fitting

The parameters of isothermal adsorption curve fitted by H-H model are shown in Table 3. The goodness of fit R^2 was greater than 0.99, indicating that the Hailwood-Horrobin model had a good fitting effect on the isothermal moisture absorption curve of six tree species. The k_1 , k_2 , and W values were calculated by combining parameters A, B, and C with Eqs. 5, 6, and 7. The parameter values are close to the fitting parameters of previous studies (Papadopoulos and Hill 2003; Zaihan *et al.* 2009). Figure 8 is the isothermal moisture absorption curve of H-H model of six tree species using the data in Table 3.

Table 3. Isothermal Adsorption Curve Parameters Calculated by H-H Model

Species	Specimen thickness (mm)	A	B	C	k1	k2	w	R ²
<i>P. asperata</i>	1	4.31	15.83	15.79	5.50	0.8161	411.6	0.9960
	4	4.32	15.44	15.97	5.27	0.8379	408.2	1.0000
	8	2.98	18.15	17.30	8.27	0.8379	416.6	0.9992
	20	1.59	21.02	18.65	16.84	0.8346	426.1	1.0000
<i>P. deltoides</i>	1	4.40	16.87	16.62	5.72	0.8129	432.4	0.9986
	4	5.43	13.01	14.42	3.91	0.8246	395.4	0.9999
	8	4.05	16.37	16.52	5.83	0.8362	416.7	0.9997
	20	2.51	19.82	18.27	10.49	0.8337	432.0	1.0000
<i>Z. schneideriana</i>	1	5.33	11.45	12.70	3.66	0.8064	360.8	0.9984
	4	3.82	16.39	16.69	6.05	0.8499	411.9	0.9998
	8	3.15	18.33	18.07	7.77	0.8590	427.4	0.9996
	20	1.88	21.30	19.48	14.32	0.8507	441.0	1.0000
<i>Carpinus L</i>	1	4.90	15.17	15.93	4.74	0.8284	419.2	0.9977
	4	5.10	14.33	15.69	4.34	0.8424	412.6	0.9996
	8	4.23	17.11	17.72	5.73	0.8549	438.2	0.9994
	20	2.21	22.01	20.40	12.67	0.8537	464.1	1.0000
<i>Quercus spp.</i>	1	3.85	15.35	14.94	5.93	0.8089	388.5	0.9984
	4	4.92	15.28	16.25	4.71	0.8375	423.5	0.9998
	8	3.18	20.15	19.61	8.39	0.8575	460.8	0.9995
	20	2.08	22.99	20.93	14.06	0.8458	477.1	1.0000
<i>X. melanoxylon</i>	1	4.29	12.77	11.80	5.02	0.7405	344.0	0.9983
	4	2.81	18.51	16.59	9.24	0.7993	414.0	0.9999
	8	3.26	19.21	17.61	8.29	0.8065	440.5	0.9999
	20	1.11	24.67	20.86	28.32	0.8157	476.6	0.9984

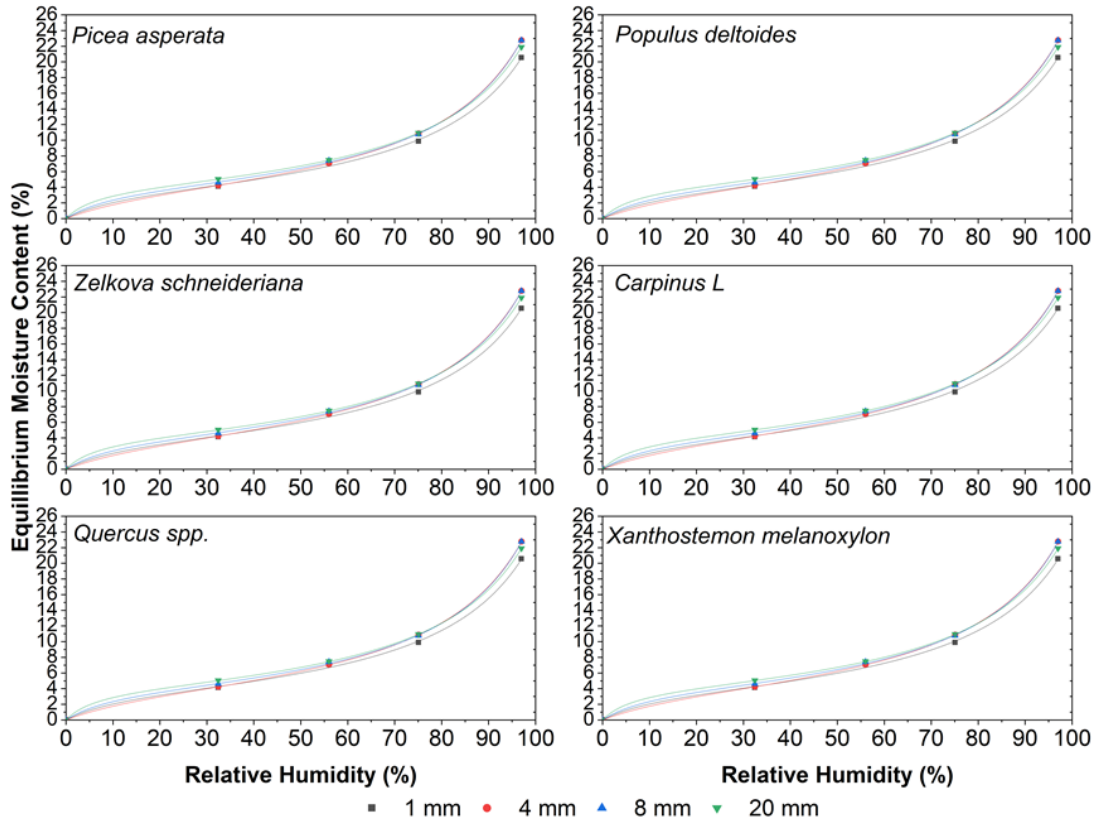


Fig. 8. Isothermal moisture absorption equilibrium moisture content change curve of six tree species

Difference of Water in Different Components of Six Kinds of Wood

The monolayer molecular adsorption and multilayer molecular adsorption calculated according to the fitting parameters of H-H model are shown in Figs. 9 and 10. According to the model calculation, the adsorbed water of monolayer molecules increased rapidly at first, and then the increase slowed down. The main rising stage is in stage A; the amount of water adsorbed by multilayer molecules increased slowly at first and then rapidly. The main increase stage is in C and D stages. The reason is that at lower RH (0 to 15%) (Xie *et al.* 2011), the adsorption sites on cellulose and hemicellulose in wood first combine with water molecules to form monolayer molecular adsorbed water, and then the monolayer molecular adsorbed water again combines with water molecules to form multilayer molecular adsorbed water.

With the four stages of hygroscopicity, the adsorbed water amount of monolayer of samples with four thicknesses gradually became close, and the monolayer molecular adsorption water of 1mm *Quercus* spp. samples, 1 mm and 4 mm *X. melanoxylon* samples were gradually greater than that of larger thickness samples, which may be due to the moisture absorption and moisture movement of wood to the interior, and the hydrogen bond fracture between macromolecules in the cell wall generates new adsorption sites,.

After the macromolecular hydrogen bond breaks, water molecules can enter deeper into the wood cell wall and bind to the deep adsorption sites (Hartley *et al.* 1992). When water enters the thicker sample through more pore structures, it will be difficult for water to enter deeper into the wood. In addition, the density of tree species is high, and there are more substances and fewer pores in it. When the closely arranged cellulose molecular chains are opened, relatively more adsorbable sites will be produced.

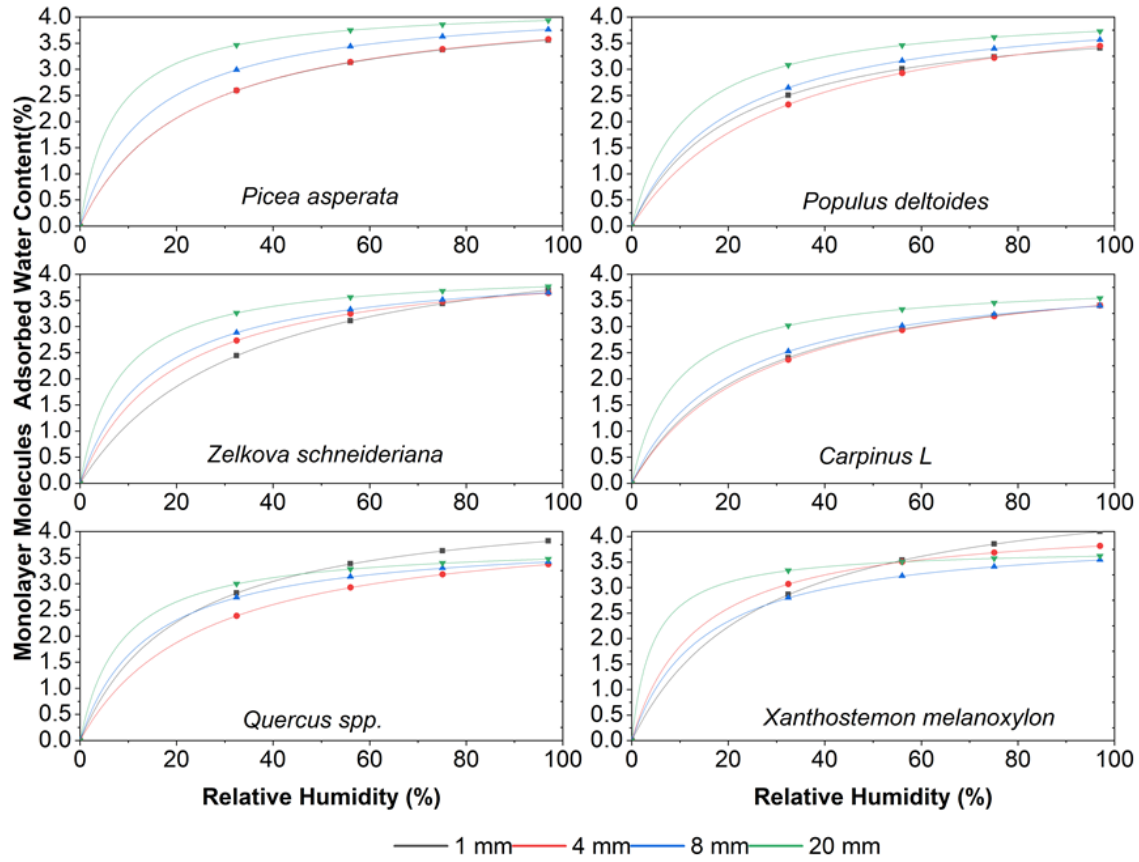


Fig. 9. Monolayer molecular adsorption curves of six tree species

Figure 10 shows that the multi-layer molecular adsorption water of *P. asperata* and *P. deltoides* under the same RH condition first increased and then decreased with the increase of sample thickness, and the multi-layer molecular adsorption water of the other four tree species decreased with the increase of sample thickness. This is consistent with the explanation of the relationship between EMC and thickness of the above six tree species, which is mainly that the high density of tree species, high extract content and the increase of sample thickness limit the wood expansion and affect the multi-layer molecular adsorption water of wood.

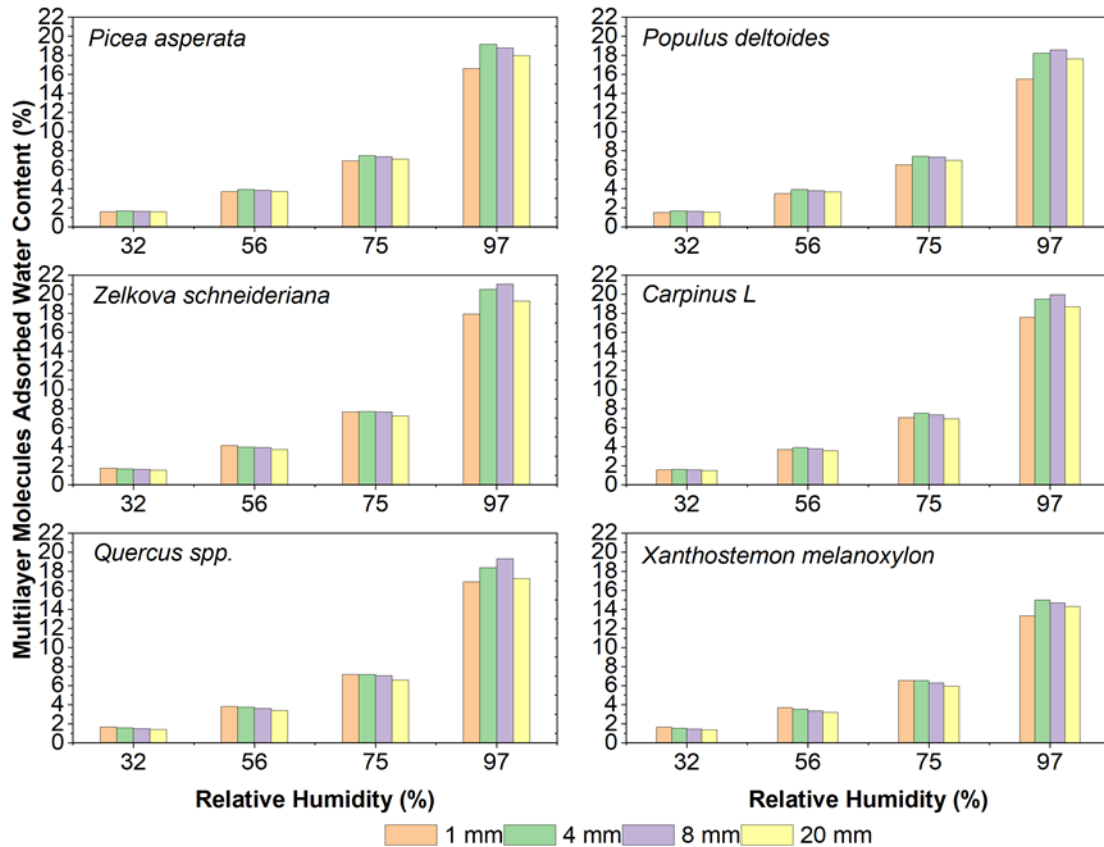


Fig. 10. Relationship between multilayer molecular adsorption of six tree species and sample thicknesses

CONCLUSIONS

1. The equilibrium moisture content (EMC) of coniferous *Picea asperata* was found to be higher than that of broad-leaved *Populus deltoides*, and the EMC of five broad-leaved tree species increased first and then decreased with the increase of wood density. The moisture absorption extent of coniferous wood was the highest, and the moisture absorption decreased with the increase of density and thickness of broad-leaved wood. Thus, the EMC and moisture absorption of wood are obviously related to the chemical composition content, density, and sample thickness of tree species.
2. The Hailwood Horrobin (H-H) model was found to better fit the isothermal moisture absorption curves of six kinds of trees with four kinds of thickness. The amount of water adsorbed by wood monolayer and multilayer molecules is related to the thickness of tree species and samples, and the change of water adsorbed by multilayer molecules is consistent with the change of wood EMC.
3. When drying wood with different thicknesses, the final moisture content should be controlled separately. The dry wood should be stored in the warehouse in time to avoid the impact of changes in ambient temperature and humidity. The production process should be shortened as soon as possible during product processing to avoid long-term production.

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