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A study on one-dimensional isothermal moisture migration in *Pinus yunnanensis*

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Abstract: In this study, in order to acquire the quantitative distribution of wood moisture in a hygroscopic environment, *Pinus yunnanensis* was taken as the research target. In consideration of the phase equilibrium relationship among vapor and bonded water, unstable diffusivities of vapor and bonded water, and the relationship between the equilibrium moisture content of wood and surrounding moisture content, a model of one-dimensional isothermal moisture migration in wood was established beneath the fiber saturation point. Comparative analyses were then carried out on the model solution and experimental measurement results. It was found that the model could accurately predict the process of moisture migration in the wood in each hygroscopic range beneath the fiber saturation point, and the diffusivities of bonded-water D_{ls} and vapor D_{vs} increased with greater moisture content (MC) of wood, but they could be regarded as constant within a certain MC range. The larger the gap change range between the initial wood MC and surrounding equilibrium MC was, the greater the MC gradient of the wood interlayer would be, and the shorter the overall EMC time would be. Environment boundary was selected as the actual EMC of wood under the corresponding ERH.

Keywords: *Pinus yunnanensis*, One-dimensional isothermal migration, Moisture content gradient, Equilibrium moisture content

INTRODUCTION

In the relevant standards of each nation, the "wood moisture content" used for investigating wood mechanical properties actually refers to the equilibrium moisture content (EMC) of the wood with a specific test environment temperature and humidity, which is usually set as the constant temperature and humidity environment with the temperature (T) of 20℃ and relative humidity (RH) of 65%. However, the bearing wood materials actually used are in an environment with dynamic changes in temperature and moisture content. When the influence of temperature on the wood mechanical properties is seen as a constant in the constant temperature range, the dynamic changes in the surrounding moisture content lead to uneven moisture distribution inside the wood, such as gradient moisture distribution, which seriously affects the bearing capacity of the wood [1, 2, 3]. Therefore, it is required to determine a scientific mathematical expression of wood moisture distribution state, in order to analyze the wood moisture distribution state and the relationship with wood mechanical properties.

Compared with general non-hygroscopic porous materials, wood is characterized by porosity but a low effective conduction rate, high moisture content (water vapor, bonded water and free water), significant material anisotropy, and uneven structure [4, 5]. Combined with imperfect direct testing techniques and means of wood moisture distribution [6, 7, 8], difficulties are determined in the wood moisture migration mechanism and mathematical simulation. For example, in terms of water vapor (in the wood cell cavities), bonded water (in the wood cell walls) and free water (in the wood cell cavities), a series of problems will occur in the migration process, such as phase change, great difference in migration rate along different wood texture directions, migration rate changing with wood moisture content, and complex heat and mass transfer at the wood-environment boundary [5, 9, 10, 11].

Under the premise of vapor-bonded water phase equilibrium relationship, unstable diffusivities of vapor and bonded water, as well as the relationship between wood EMC and surrounding moisture content (SMC) considered in this paper, a one-dimensional isothermal migration model of wood moisture is established beneath the fiber saturation point. Then, analyses are carried out on the migration laws of wood moisture in different hygroscopic ranges, the relationship between

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diffusivities of the vapor-bonded water and wood moisture content (MC), as well as other issues, and these are verified by experiments.

NUMERICAL SIMULATION

Description of wood isothermal moisture absorption process (physical model)

In a constant temperature convection environment, once the wood with moisture content beneath the fiber saturation point is placed in the environment with a surrounding equilibrium moisture content that is higher than the wood EMC, then immediate moisture migration occurs to the surrounding moisture at the environment-wood interface and in the wood. Its process is shown as follows. (1) The wood surface vapor (in the wood cell cavities) density is lower than the surrounding vapor density, and the water vapor is transferred from the environment to the wood surface by means of convective mass transfer between the environment and wood interface. Meanwhile, the water vapor in the cell cavities and environment is absorbed by the wood surface-layer cell wall and converted to liquid water, until phase equilibrium between the bonded water and water vapor is reached. (2) After the wood surface absorbs water, the water vapor density in the cell cavities will be greater than that in the wood inner cell cavities, and the water content absorbed by the cell walls will be greater than in the wood inner cell walls. In the driving of the density difference, the water vapor migrates from the surface wood cell cavity to the inner wood cell cavities by means of diffusion, while the bonded water migrates from the surface wood cell walls to the wood inner cell walls in the driving of the capillary force. Similarly, the bonded water in the wood cell walls and water vapor in the cell cavities is always in the dynamic phase equilibrium during the migration process. (3) The inward migration of the surface water vapor and bonded water mass is compensated by the direct input of surrounding water vapor and the condensation on the cell walls.

Therefore, the surrounding water vapor migrates from the wood surface to the wood inner cell walls through the above process, until an equal moisture content between the outer and inner wood is reached. Meanwhile, the wood moisture content under this environment is wood EMC.

Governing equation

Governing equation of liquid water (bonded water)

Wood is considered as a network porous material composed of large and small capillaries, of which the cell walls are connected, and the same is true for the pores. Then the governing equation of bonded water [5] can be expressed as shown below:

$$\frac{\partial W}{\partial \tau} = D_{ls}\frac{\partial^2 W}{\partial z^2} - \frac{\dot{m}_v}{\rho_d} \quad (1)$$

Governing equation of water vapor

The existence of the wood internal air is ignored (except when calculating relative air humidity), regardless of air mass migration [5], then:

$$\dot{m}_v = \Phi\frac{\partial \rho_V}{\partial \tau} - D_{Vs}\frac{\partial^2 \rho_V}{\partial z^2} \quad (2)$$

Phase equilibrium governing equation of liquid water and vapor

When the moisture content is unable to reach the surrounding equilibrium EMC, the water vapor in the wood cell cavities is always unsaturated water vapor, of which the pressure p and local wet air relative humidity φ should satisfy the following:

$$p_v = p_{sv}\varphi \quad (3)$$

Under atmospheric pressure, due to the low water vapor density in the wood cell cavities, it is close to the ideal gas, which can be assumed to satisfy the ideal gas equation:

$$\rho_v = p_v\frac{M_V}{RT} \quad (4)$$

Wood moisture content W, relative humidity φ and temperature t simultaneously satisfy the Simpson model [12] (to facilitate calculation, the inverse function is used herein):

$$\varphi = f_p^*(t, W) \quad (5)$$

Boundary conditions

Boundary conditions of wood surface and surrounding moisture exchange

The water vapor in surrounding wet air is attached to the wood surface in the form of condensation, thus the water vapor condensation rate $\dot{m}_s$ on the wood surface is as shown below [5]:

$$\dot{m}_s = h_m^*(W_e - W_s) \quad (6)$$

Then, the mass exchange boundary condition of the wood surface and surrounding wet air is expressed as follows [5]:

$$\frac{\partial W}{\partial \tau} = D_{ls}\frac{\partial^2 W}{\partial z^2} - \frac{\dot{m}_v}{\rho_d} + \frac{\dot{m}_s}{\rho_d \Delta z} \quad (7)$$

In Eq. (6), W_e is the maximum actual equilibrium moisture content of the wood in the environment, rather than the theoretical maximum moisture content of the wood converted by the Simpson model.

Boundary conditions of wood inner

The wood inner moisture is composed of bonded water on the wood cell walls of the adjacent layers through diffusion, and water vapor in the wood cell cavities of the adjacent layers through diffusion; therefore:

$$\frac{\partial W}{\partial \tau} = D_{ls}\frac{\partial^2 W}{\partial z^2} + \frac{\dot{m}_v}{\rho_d} \quad (8)$$

EXPERIMENT ARRANGEMENT

Instruments and devices

(1) A Binder KMF720 climate chamber ((Gesellschaft Mit Beschrankter Haftung)) with temperature accuracy of 0.1℃ and humidity accuracy of 1.5%.

(2) A digital electronic balance with a range of 500 g and precision of 0.01 g.

(3) A digital vernier caliper with a precision of 0.01 mm.

Experimental methods

Moisture absorption experiment of specimen

The research targets are six specimens of *Pinus yunnanensis* with the dimensions (length× width×thickness) of 480 mm × 20 mm × 20 mm, and side sealed by aluminum foil along the thickness direction (Fig. 1). These are placed into the constant temperature and humidity box, in which T = 20℃ and RH = 42%. When the equilibrium in the specimen mass and environmental humidity (no changes in mass by weighting for three consecutive days) is achieved, then the RH is adjusted to 65%, 80% and 90% in turn. In the three moisture absorption ranges of RH = 42-65%, 65-80% and 80-90%, the specimen mass is weighted every day at 9 am and recorded, until the specimen mass no longer changes.

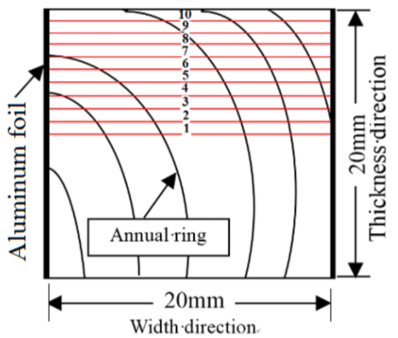

Fig.1. Specimen preparation

Measurement and determination of specimen D_s, D_{ls} and D_{vs} values

For the D_{ls} and D_{vs} values of the *Pinus yunnanensis* specimens with EMC less than 10%, refer to Reference 5. The bonded water diffusivities D_{ls} of *Pinus yunnanensis* with other moisture contents are calculated for integer according to Eq. (9) [5].

$$D_{ls} = 0.5\times10^{-10} + \frac{W-0.1}{W_{fsp}-0.1}\times0.78\times10^{-10} \quad (9)$$

In this experiment, three moisture absorption ranges of *Pinus yunnanensis* are calculated by

Empirical Eq. (9), and verified by the Crank method in Reference 11 with measured tests. Finally, it is comprehensively considered to take $D_{ls}=5.0\times10^{-11}$ m^2/s (RH42%-65%), $D_{ls}=6.0\times10^{-11}$ m^2/s (RH65%-80%) and $D_{ls}=6.0\times10^{-11}$ m^2/s (RH80%-90%).

The water vapor diffusivity D_{vs} of *Pinus yunnanensis* is measured according to *ASTM E96 / E96M - 05 Standard Test Methods for Water Vapor Transmission of Materials*. The values are $D_{VS}=0.7\times10^{-6}$ m^2/s (RH42%-65%), $D_{VS}=1.5\times10^{-6}$ m^2/s (RH65%-80%), $D_{VS}=1.6\times10^{-6}$ m^2/s (RH80%-90%).

DEFINITE CONDITION AND SOLUTION

Definite condition

The specimen thickness is divided into 20 layers, then Δz = 1 mm (as shown in Fig. 1), and the calculation step $\Delta\tau$ = 600 s. Among them, the absolute dry density of *Pinus yunnanensis* ρ_d = 519.74 kg/m^3 (measured), that of the cell wall material is 1540 kg/m^3 [12], material surface mass transfer coefficient h_m*= 3.88 x 10^{-6} *kg/(m^2·s)* [5], and molar gas constant R = 8.315 *J/(mol·k)*; for the bonded-water diffusivity D_{ls} and water vapor diffusivity D_{vs} in *Pinus yunnanensis,* refer to Section to *Experimental methods*

Solution of partial differential equation

Differential Eqs. (1-7) are transformed into explicit difference equations, and according to the above definite conditions, the moisture absorption laws of *Pinus yunnanensis* in each moisture absorption range can be obtained.

Considering the specimen geometry symmetry in this study, moisture migration is only solved within half specimen thickness (as shown in Fig. 1).

RESULTS AND ANALYSIS

Wood moisture absorption process and model validation

Based on the above mathematical model, definite condition and difference numerical method, the theoretical moisture content change curves of *Pinus yunnanensis* (solid squares in Figs. 2-4) in three moisture absorption ranges (RH = 42-65%, 65-80% and 80-90%) can be obtained. However, the measured average moisture content curves of six *Pinus yunnanensis* specimens (hollow triangles in Figs. 2-4) consistently prove that this theoretical model can accurately reflect the wood moisture absorption process.

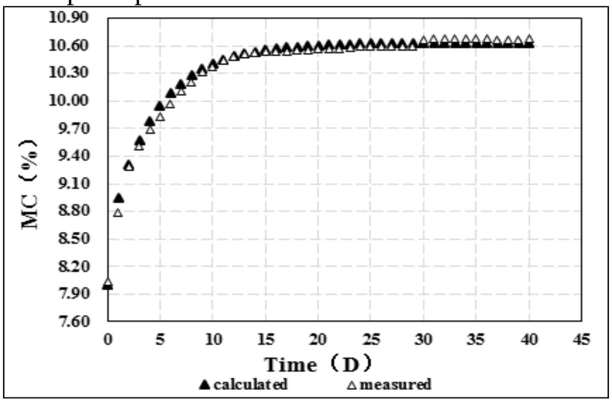

Fig. 2. MC-change curve of YNP along with time under RH42-65% environment.

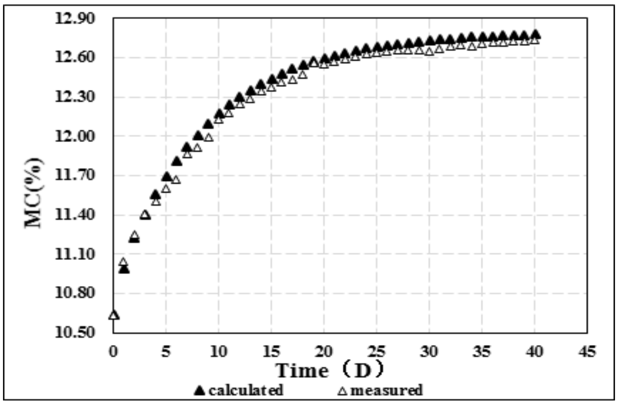

Fig. 3. MC-change curve of YNP along with time under RH65-80% environment

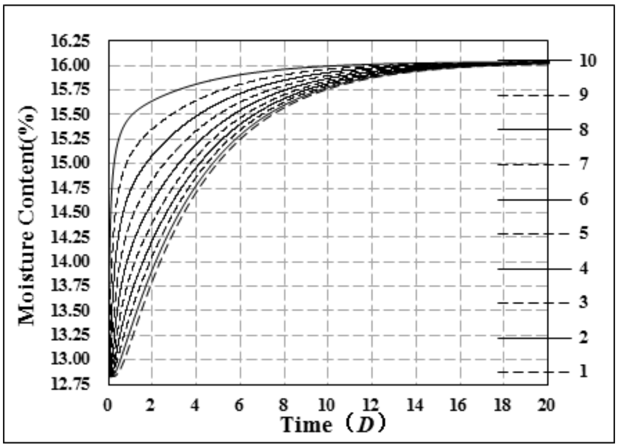

Fig. 4. MC-change curve of YNP along with time under RH80-90% environment

It also can be seen from Figs. 2-4 that the wood materials have different moisture absorption rates in different moisture absorption ranges (corresponding to the different wood moisture contents and moisture states). As a result, in the three moisture absorption ranges of RH = 42-65%, 65-80% and 80-90%, *Pinus yunnanensis* respectively requires 30 d, 40 d and 25 d for moisture absorption to achieve a basic balance of water inside and outside respectively, i.e. to reach the equilibrium moisture content (EMC) under the target environment humidity. The reasons resulting for differences are as follows:

(1) In the above three moisture absorption ranges, the actual change ranges of moisture content in *Pinus yunnanensis* are 7.95-10.63%, 10.63-12.80% and 12.80-16.04%, i.e. the moisture content gradient differences are 2.68%, 2.17% and 3.24%, respectively. Therefore, the moisture content gradient difference is able to directly determine the above moisture absorption rates of *Pinus yunnanensis.*

(2) In the process of wood moisture absorption, the cell walls present a certain degree of swelling, thus leading to greater pit aperture, and the adsorption capacity of wood cell wall weaken gradually, so that the diffusivity of vapor (DOV) is increased to a certain degree [5,11] (as shown in Fig. 5).

(3) In a certain range of moisture content, with the increase of moisture content, the channel capacity of the micro capillary system in the wood cell walls is also enhanced to a certain degree, thereby resulting in the diffusivity of bonded water (DBW) also increasing [1] (as shown in Fig. 5).

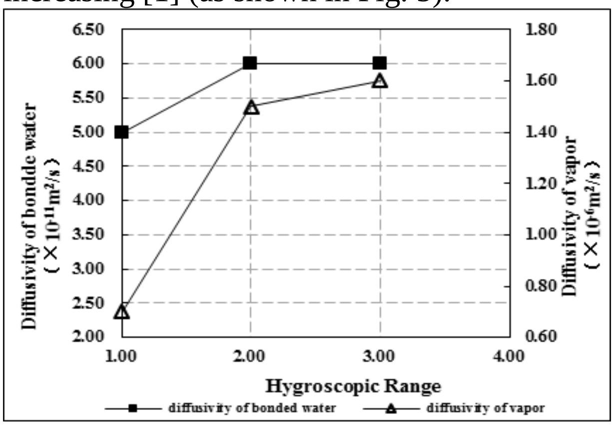

Fig. 5. Diffusivities of bonded-water and vapor in different hygroscopic ranges.

The relationship of the diffusivities of the wood bonded water and water vapor with wood moisture content is still inconclusive in academia at present, and thus requires further research.

Distribution of wood moisture content in moisture absorption process

Figs. 6, 8 and 10 respectively show the changes of moisture content in each layer of the *Pinus yunnanensis* specimens over time within three moisture absorption ranges during moisture absorption process, of which Layer 1 is the middle layer of the specimen, and Layer 10 is the boundary layer connected with the environment (see Fig. 1).

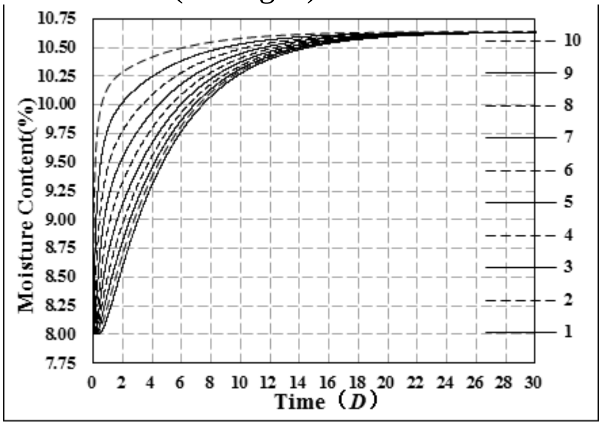

Fig. 6. MC distributions among different layers of YNP along with time under RH42-65% environment.

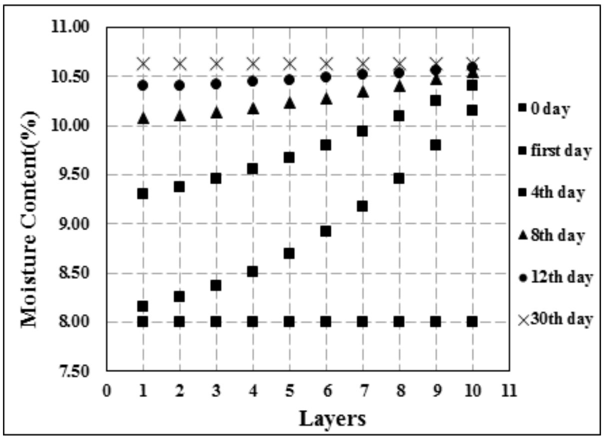

Fig. 7. MC gradients among different layers and time of YNP under RH42-65% environment.

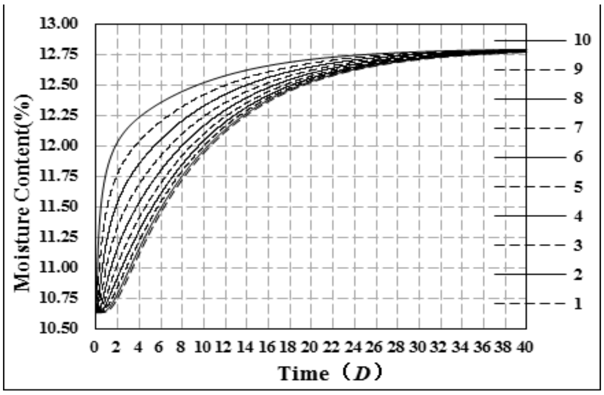

Fig. 8. MC distributions among different layers of YNP along with time under RH65-80% environment

Figs. 7, 9 and 11 respectively show the changes in the moisture content gradient of each layer on days 0, 1, 4, 8, 12 and 30 in the three moisture absorption ranges.

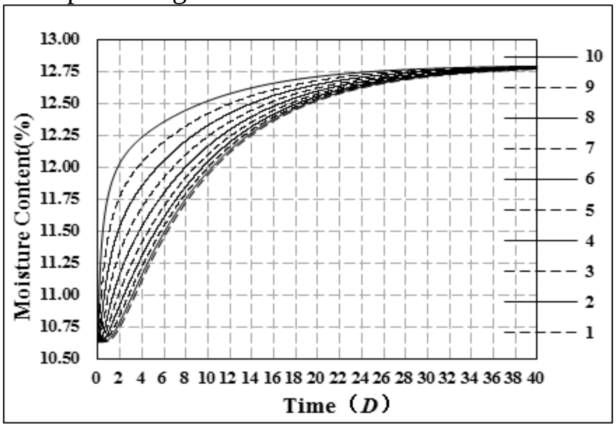

Fig. 9. MC gradients among different layers and time of YNP under RH65-80% environment.

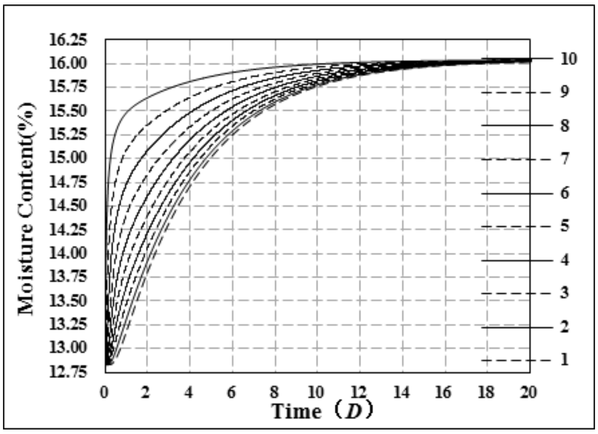

Fig. 10. MC distributions among different layers of YNP along with time under RH80-90% environment.

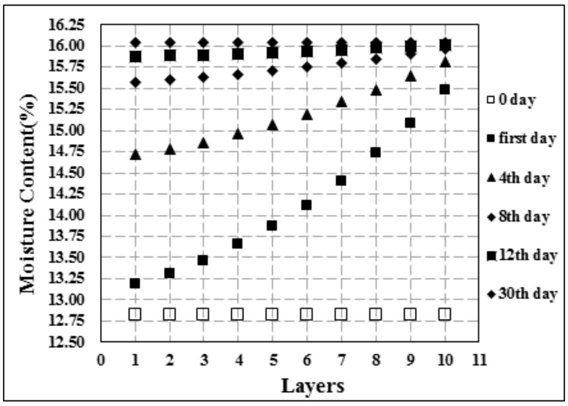

Fig. 11. MC gradients among different layers and time of YNP under RH80-90% environment

It is shown in Figs. 6 and 11 that the larger the change range of wood moisture content is, the faster the moisture content response of each layer especially the surface will be, and thus the greater

Table 1. Relationship between RH of environment and EMC of *Pinus yunnanensis*

Ambient relative humidity	%	42	65	80	90
Actual equilibrium moisture content of *Pinus yunnanensis*	%	7.95	10.63	12.80	16.04
Maximum theoretical equilibrium moisture content of *Pinus yunnanensis* calculated by Simpson model	%	8.00	12.00	16.05	20.54

the moisture absorption rate will be, the greater the gradient difference of inter-layer moisture content will be, the faster the rate of moisture content of each layer to achieve EMC will be, and the shorter the time will be.

Therefore, setting up an appropriate change range of wood moisture content and control proper drying rate in wood drying process is an essential way to prevent the excessively large moisture content gradient difference of internal and external wood layer from cracking.

Relationship between wood EMC and surrounding RH

It can be seen from Table 1 that the EMC of *Pinus yunnanensis* under various surrounding RH is not equal to the theoretically calculated EMC [12], and along with the increase of surrounding RH, differences also become greater. Therefore, in the solution of the wood moisture migration model, its environmental boundary W_e should be the actual EMC of wood under this surrounding RH, rather than the theoretical wood EMC calculated by the Simpson model. Otherwise, larger errors occur in the model calculation of required equilibrium time in the setting environment, as well as the size and distribution of moisture content gradient.

CONCLUSIONS

(1) The wood one-dimensional isothermal moisture migration model can accurately predict the wood moisture migration process in each moisture absorption range beneath the fiber saturation point.

(2) The diffusivities of wood bonded water D_{ls} and water vapor D_{vs} increase with greater moisture content, but are considered as constants within a certain moisture content range.

(3) The larger the change range of the gap between initial wood moisture content and surrounding equilibrium moisture content is, the greater the moisture content gradient of wood inter-layer in the dynamic moisture migration process will be, and the shorter the time to reach overall targeted EMC will be.

(4) The environmental boundary W_e should be set as the actual EMC of the wood under this surrounding RH.

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Nomenclature

D_{ls} —Diffusivity of liquid water in wood, m^2/s;
D_{vs}—Mass diffusivity of vapor in wood, m^2/s;
f_p—Inverse function relation of Simpson model;
h_m^*—Surface mass transfer coefficient, $kg/(m^2\cdot s)$;
$\dot{m}_V$ —Volume evaporation rate, $kg/(m^3\cdot s)$;
$\dot{m}_s$ —Wood surface evaporation/condensation rate, $kg/(m^2\cdot s)$;
p_{sv}—Saturated vapor pressure, p_a;
p_v—Unsaturated vapor pressure, p_a;
R—Molar gas constant, $J/(mol\cdot K)$;
t—Temperature, ℃;
T—Thermodynamic temperature, K;
W — Wood moisture content, %, kg/kg or kg/m^3;
W_e —Equilibrium moisture content of wood environment, kg/m^3.
W_s—Wood surface moisture content, kg/m^3;
Z —Specimen thickness, *mm*

Greek symbols
ρ_v— Vapor density, i.e. absolute humidity, kg/m^3;
ρ_d—Absolute dry density of wood, kg/m^3;
τ— Time, s;
Φ—Wood void fraction
φ —Relative air humidity, %;

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