WOOD RESEARCH
62 (6): 2017
831-838

MODEL OF FREE WATER IN WOOD

Richard Hrčka
Technical University in Zvolen
Faculty of Wood Sciences and Technology
Zvolen, Slovak Republic

(Received September 2017)

ABSTRACT

The derived model describes equilibrium in wood as it is placed it water. The model expresses the equality of density of water and coupled term of basic density and moisture content on the other side. The other part of the model is its extension to water in wood. The maximum moisture content is derived from the view point of density definition. Then Archimedes' principle enables to measure bound water maximum moisture content. The model is applicable to wood of arbitrary wood species and also for different kind of materials as it is documented in the embedded table.

KEYWORDS: Model, free water, moisture content of wood, basic density.

INTRODUCTION

The demand for water environment of wood is found as good in the field of research practice as in the field of wood industry. There are many examples wood contains water, air and substance in the laboratory. Wood in equilibrium with surrounding receives and releases equal amount of water in surrounding. Water in wood is presented as bound and free water (Stamm 1964, Skaar 1972). Both of them are recognized by observer during their transport through wood. The procedure of recognizing bound and free water in wood during soaking was developed by Babiak and Kúdela (1988). They applied the procedure of wood double weighing during its non-equilibrium and they supposed the local thermodynamic equilibrium for wood during soaking. Similar assumption has been well-known from continuum mechanics as is described by Brdička et.al. (2011). Moreover, Babiak and Kúdela (1988) documented the experimental prove of equality of water density in wood and surrounded water during soaking. They concluded that density of bound water is density of surrounded water and also free water density. The water density value of 1 $g \cdot cm^{-3}$ was used by Ugolev et al. (1984). Stamm (1964) published value of bound water density higher then free water according to pycnometric measurements. Later on, Skaar (1972) corrected the value to be closely free water density. The idea for higher value of bound water density then surrounded water density is supported in diagram for wood density dependence on its moisture content published by Kollmann (1951), Požgaj et al. (1993). The diagram contains the parallel line with moisture content axis at oven dry density of 1200 kg·m^{-3}. The previous results do not coincide very well. Common feature of both experiments is wood mass measurement in water environment. The measurement impossibility of water mass as it is weighed in water is the key point of the observation. The same is valid for free water. Therefore free water in wood must be modelled to be recognized.

The aim of the contribution is model of free water in wood, its application to deriving formula for maximum moisture content, indirect determination of cells' walls saturation limit and describing the method for their measurement.

MODEL

Density ρ of matter is its mass in unit of its volume. Concentration c of a compound in a mixture is a compound mass in mixture volume. Let the equal numbers of water molecules enter and exit the wood volume during soaking. Wood and water are in equilibrium.

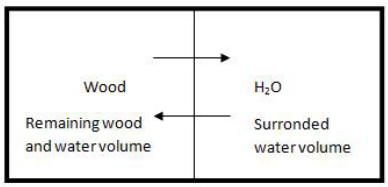

Fig.1: The concept of wood and water equilibrium.

The boundaries between wood and water are distinct. The intensive parameters of wood and water in equilibrium are equal. The concentration of water molecules in surrounded water volume is equal to its density (abbreviate as water density ρ_{H2O}). The concentration of wood substance mass in remaining wood and water volume is equal to concentration of water molecules in surrounded water. The concentration of wood substance mass in remaining wood and water volume is water density. From the other side the definition of basic density is required. For example, the definition of basic density can be found in the literature (Grundelius 1990, Požgaj 1993). Basic density ρ_{rc} is a concentration of oven dry wood mass in wood green volume. Therefore basic density of wood, only composed with cell wall and in equilibrium with surrounded water, is equal to water density. There is only one possibility how to add the other substance to system without alteration the densities. The densities must be equal. The bound water density is water density. As far as free water is connected with surrounded water in equilibrium, its density is also water density. The Fig. 2 depicts the situation of free water in wood.

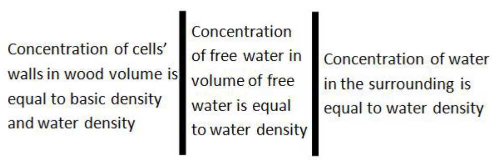

Fig.2: The scheme of free water in wood in equilibrium with water.

The Eq. 1 expresses the model of free water in wood as wood is in equilibrium with water.

$$\rho_{H_2O} = \rho_{rc}\left(1 + w_{Fmax}\right) \quad (1)$$

The symbol w_{Fmax} is moisture content of free water in wood as wood is in equilibrium with water (abbreviated as maximum free water moisture content). The Eq. 1 represents the sum of two concentrations in the volume which is equal to the sum of two mentioned volumes, surrounded water volume and remaining wood and water volume. The value of maximum free water moisture content is expressed in equation 2.

$$w_{Fmax} = \frac{\rho_{H_2O}}{\rho_{rc}} - 1 \quad (2)$$

The Eq. 2 reflects and summarized the previous statements about free water in wood. Also Eq. 2 is a base for evaluation of cells' walls saturation limit as a difference of the maximum moisture content and maximum free water moisture content.

MAXIMUM MOISTURE CONTENT W_{MAX}

The density of wood is valid characterized only at mentioned moisture content. This is also valid for density at maximum moisture content ρ_{max}. The basic density connects these two expressions as is indicated in Eq. 3.

$$\rho_{max} = \rho_{rc}\left(1 + w_{max}\right) \quad (3)$$

From the other side, density at maximum moisture content is expressed as ratio of wood maximum mass in a unit of wood green volume. Wood maximum mass is a sum of wood substance and water in wood masses. Wood green volume is a sum of wood substance and water in wood volumes. The density of water in wood is water density. The Eq. 4 expresses the maximum moisture content.

$$w_{max} = \left(\frac{1}{\rho_{rc}} - \frac{1}{\rho_s}\right)\rho_{H_2O} \quad (4)$$

The symbol ρ_s is wood substance density.

The indirect determination of cell wall saturation limit w_{CWS} is subtraction between maximum moisture content and maximum free water moisture content (Eq. 5).

$$w_{CWS} = 1 - \frac{\rho_{H_2O}}{\rho_s} \quad (5)$$

Cell wall saturation limit characterizes the bound water maximum moisture content. Primary definition was published by Ugolev (1984) in the form of the equation. The definition was also mentioned by Babiak and Kúdela (1995). Cell wall saturation limit is the soaked wood cell maximum moisture content (Požgaj et al. 1993).

THE MEASUREMENT OF CELL WALL SATURATION LIMIT

The gravitational force, buoyancy force from Archimedes' principle and force from balances act on wood, which is immersed in water. Because equilibrium of wood and water is present and no net force is a result as the sum of these acting forces on the same line, Eq. 6 is written.

$$m_{max} = \rho_{H_2O}V_{max} + m_{zmax} \quad (6)$$

The symbol mmax denotes maximum mass of wood specimen, V_{max} is specimen's green volume, mzmax is specimen's apparent mass which multiplication with acceleration due to gravity is equal to the opposite force exerted by the balances on the wood specimen. The division of Eq. 6 with nonzero oven dry mass m_0 and performing equivalent procedures result in expression of the maximum moisture content, Eq. 7.

$$w_{max} = \frac{\rho_{H_2O}}{\rho_{rc}} - 1 + \frac{m_{zmax}}{m_0} \quad (7)$$

It follows that apparent mass in equilibrium is maximum mass of bound water and its ratio with oven dry mass is cell wall saturation limit. Moreover, the subtraction of displaced water mass and oven dry mass is free water mass at equilibrium.

The using of balances is not only the method of mass measurement. Mass m, as an inertia property, is involved in transport phenomena. The Eq. 8 of wood motion in water comes from Newton's laws of motions, Archimedes' principle and Darcy's law. It should be noted, that mass is constant when specimen moves at velocity v in time t.

$$m\frac{dv}{dt} = mg - V\rho_{H_2O}g - bv \quad (8)$$

Volume V is green volume, constant b characterize the friction between specimen surface and water.

The velocity and later on coordinate x of specimen during motion is the solution of Eq. 8. The coordinate x is convenient to express in time and velocity, Eq. 9.

$$x = \frac{g}{b}\left(1 - \frac{m_{vv}}{m}\right)\left(t - \frac{\left(1 - e^{-bt}\right)}{b}\right) = v_\infty t - \frac{v}{b} \quad (9)$$

The zero initial conditions are involved in solution 9. The steady state velocity v∞ is used to compute the position of specimen x_{steady} during linear uniform motion according to asymptote to solution of Eq. 8. The simulation of Eq. 9 is embedded in Fig. 3. The wood substance density of 1.54 g·cm^{-3} and beech wood density of 1.199 g·cm^{-3} at maximum moisture content of 1.10 come from the publication of Požgaj et al. (1993). Parameter b was set to value of 3.10 s^{-1}.

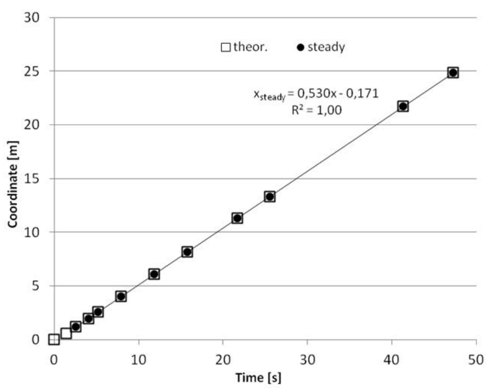

Fig. 3: The coordinate as a function of time, also during steady state motion.

The parameters of linear function served as help step for determination of density at maximum moisture content and parameter b. As velocity at steady state does not change, the specimen has constant density.

POSSIBLE SITUATIONS FOR DIFFERENT KIND OF MATERIALS IMMERSED IN WATER

The equilibrium of wood in water is only special case of possible equilibriums of the other materials in different liquids. The Tab. 1 contains the relative positions of objects in liquids in uniform gravitational field.

Tab. 1: Arrangement possibility of object and liquid interaction.

Possible situation		$1-\frac{\rho_L}{\rho_s}<0$	$1-\frac{\rho_L}{\rho_s}=0$	$1-\frac{\rho_L}{\rho_s}>0$
		$\frac{m_{z\max}}{m_0}<0$	$\frac{m_{z\max}}{m_0}=0$	$\frac{m_{z\max}}{m_0}>0$
$\frac{\rho_L}{\rho_{rč}}-1<0$	$\frac{m_{vv}}{m_0}-1<0$	Impossible $w_{max}<0$	Impossible $w_{max}<0$	Real situation if $w_{max}\geq 0$
$\frac{\rho_L}{\rho_{rč}}-1=0$	$\frac{m_{vv}}{m_0}-1=0$	Object's substance surfaces	Surrounded liquid dissolves the object	Object's substance sinks
$\frac{\rho_L}{\rho_{rč}}-1>0$	$\frac{m_{vv}}{m_0}-1>0$	Real situation if $w_{max}\geq 0$	Always possible $w_{max}>0$	Always possible $w_{max}>0$

*where ρ_L is density of liquid, m_{vv} is displaced mass of liquid.

The real situation must fulfil a condition of nonnegative maximum liquid content. It is a sum of the two expressions. One is in a head of row and the other one is in a head of column of Tab. 1. Both expressions cannot be negative if they are interpreted as masses of liquids in object.

DISCUSSION

The evaluation of wood moisture content measurement has always required at least the double measurement of mass. For example, the first measurement of oven dry mass, the second one the saturated wood mass with water. Then the task about mass measurement order is answered as wood does not solve in water.

The method for distinguishing free and bound water in wood based on Archimedes' principle was presented by Babiak and Kúdela (1988). Their method originates from definition of oven dry density ρ_0 as a ratio of oven dry wood mass to its oven dry volume. The proposed method does not need for recognizing free and bound water mass information about oven dry density. The method of Babiak and Kúdela (1988) was closely related to definition of cell wall saturation limit, which was proposed by Ugolev (1984), equation 10.

$$w_{CWS}=\left(\frac{1}{\rho_{rc}}-\frac{1}{\rho_0}\right)\rho_{H_2O} \tag{10}$$

The comparison of expressions on right sides of Eqs. 5 and 10 shows expression for free water maximum moisture content, as it was published, for example, in Wood technical handbook (1970):

$$\left(\frac{1}{\rho_0}-\frac{1}{\rho_s}\right)\rho_{H_2O}=\left(\frac{1}{\rho_{rc}}-\frac{1}{\rho_{H_2O}}\right)\rho_{H_2O}=w_{Fmax} \qquad (11)$$

The hyperbolic function of w_{cws} on ρ_{rc} was shown by Ugolev (1984) as is indicated in Eq. 10. The expression of cell wall saturation limit in Eq. 5 does not explicitly depend on basic density.

Babiak and Kúdela (1988) presented the experimental evidence about equality of free and bound water density in their publication. The proposed method is based on equality of intensive parameters in equilibrium.

Babiak et al. (1989) published thermodynamic model of water in wood. They wrote and idea about lower density of water in wood due to presence of tension stress and several reasons for such thinking. Finally, their model contained the assumption of practically incompressible water in wood. The derived model is based on water density.

It seems the determination of bound water density is the key solution of recognizing the bound and free water in wood and also determination of maximum moisture content as the sum of previous mentioned quantities. Skaar (1972) corrected bound water density value from Stamm (1964) publication. Weatherwax and Tarkov (1968) pycnometric measurements of wood specific gravity in water and hexan environment were the base of correction of Stamm's measured water density in wood. Weatherwax and Tarkov (1968) interpreted the results from different liquids mutually. The proposed method operates only with one liquid.

CONCLUSIONS

The derived model of free water in wood is based on the assumption of equal concentrations of free water and adjacent substance in equilibrium, if water surrounds wood. The other derived quantities are maximum moisture content and cells' walls saturation limit. These quantities measurement is based on Archimedes' principle. The apparent mass coincides with the mass of bound water. The difference of displaced water and oven dry mass is equal to free water mass in equilibrium of wood and water. There are other possibilities for experimental performance of other materials and liquids in equilibrium. The dynamic method of density measurement enables the detection of the equilibrium without using balances. The balance is still good equipment for recognition of bound and free water in wood.

ACKNOWLEDGMENTS

This work was funded by the following: the Scientific Grand Agency of the Ministry of Education SR and the Slovak Academy of Sciences (Grant No. 1/0822/17 "Surface modification of wood and coating materials in order to improve stability of the wood – coating material system."). This paper has been included into the project APVV-16-0177 "Progressive modifications of the wood surface, film-forming materials and their interactions at the phase interface."

REFERENCES

1. Babiak, M., Kúdela, J., 1988: Differentiation of the free and bound water in wood in soaking, Wood Research 117: 1-11. (in Slovak)
2. Babiak, M., Kúdela, J. 1995: Contribution to the definition of the fiber saturation point. Wood Science and Technology 29: 217-226
3. Babiak, M., Pavlíková, M., Jokel, J. 1989: Thermodynamic model of water in wood. I. Basic preconditions of the model, Wood Research 120: 31-40 (in Slovak).
4. Brdička, M., Samek, L., Sopko, B. 2011: Mechanics of continuum. 4. ed. Academia, Praha (in Czech).
5. Grundelius, R. 1990: Determining the basic density of wood chips, Tappi journal, April 1990: 183-189.
6. Kollmann, F. 1951: Technology of wood and wood-based materials. Springer - Verlag, München, 1048 pp. (in German).
7. Požgaj, A., Chovanec, D., Kurjatko, S., Babiak, M. 1993: Wood structure and properties. Príroda, Bratislava, 485 pp. (in Slovak).
8. Skaar, Ch. 1972: Water in Wood. 1. ed. Syracuse, University Press, 2018 pp.
9. Stamm, A. J. 1964: Wood and Cellulose Science. Ronald Press, New York, 549 pp.
10. Ugolev, B. N., Shhedrina, E. B., Galkin, V. P. 1984: Determination of the wood cells' walls saturation limit after its shrinkage. Scientific works, Moscow State Forest University, 161: 5-8 (in Russian).
11. Weatherwax, R. C., Tarkow, H. 1968: Importance of Penetration and Adsorption Compression of Displacement Fluid, Forest Products Journal 118 (7): 44-46.
12. ****1970: Wood technical handbook. SNTL – Nakladatelství technické literatury, Praha (in Czech).

Richard Hrčka
Technical University in Zvolen
Faculty of Wood Sciences and Technology
Masarykova 24
960 53 Zvolen
Slovak Republic
E-mail: hrcka@tuzvo.sk