Modelling the Absorption Process of Water in Wood in the Transient Regime

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Abstract

The process of absorption of water by way of wood in 3-dimensions can be described mathematically by analytical solutions, whether initial conditions aren't simples e.g., when there is a profile of concentration at the beginning of a stage of absorption, only numerical model scan be used. The transport of water is then obtained below the fiber saturation point. The potential which drives the transport of the bound-water and the free-water through the wood has been considered by testing a diffusional transport model. The transient diffusion with a constant diffusivity has been tested to describe the process. Analytical solutions have been successfully used to describe the stage of absorption. A model based on numerical method with finite differences has been found to describe the process and especially when the equilibrium of absorption has not been attained and diffusion coefficient parameter in the models was obtained by fitting the model predictions with the experimental data. Finally, water absorption of the studied wood was proved to follow the kinetics of a transient regime.

Keywords: Wood; Water absorption kinetics; Transient regime; Modeling

Introduction

The movement of moisture through is very complex process. Moisture in wood exists in three basic forms: bound water within the cell wall, free water in liquid form, as well as water vapor, in the voids of the wood. In general, water can move through wood in three forms: as water vapor through the cell cavities and permanent pores, as bound water in the wood substance and as free liquid water in the same structure [1-10].

When the surrounding atmosphere air, the moisture content is below the fiber saturation point, this fiber saturation point being attained when the relative humidity of air is 100%. When the surrounding medium is water, the moisture content is beyond the fiber saturation point [11,12].

Many studies have been made concerning the transport of moisture below the fiber saturation point. Very often, the transport of water is describing bed in terms of diffusion, the gradient of moisture content being considered as the driving force. In this case, the bound water and water vapor diffuse [13-18].

The problem of the water above the fiber saturation point is of high interest, because the presence of free water in wood drastic cally in creses its susceptibility as well as the development of fungal attacks [19,20]. However, few studies have been in this case. This problem being said to the somewhat more complicated because of the presence of free water in addition with the bound water and water vapor [21,22].

The main objective of this study is to describe the process of absorption of water, when the moisture is he beyond the fiber saturation point. The wood sample is then considered with tree directions of transport: radial, tangential and longitudinal. The second purpose of this works to build a mathematical model capable of describing the process of absorption of moisture below of saturation point, when the wood is contact with liquid water. In spite of the fact that the bound water could be transported in response to a vapor pressure gradient [23,24], we have assumed with the vast majority of wood scientists that the gradient of moisture content in the driving force for the water transport [25-29].

Materials and Methods

Theoretical basis

Assumptions: In order to clarify the problem both for the analytical treatments and numerical analysis, the following assumptions are made:

1) A tree dimensional transfer of moisture through the wood is considered.
2) These moisture transports are controlled by transient diffusion within the wood. The principal directions of diffusion are: the longitudinal, the radial and the tangential with the principal diffusivities DL, DR and DT.
3) The diffusivities are constant, as they are found from experiments.

During the step of absorption, the concentration of moisture on the wood surface reaches the equilibrium value as soon as the wood is immersed in water.

Mathematical treatment: In the axes Ox, Oy and Oz coincide with the three principal's directions of diffusion (FIG. 1), the general equation of diffusion in tree-dimensions with constant diffusivities is:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x}(D_L \frac{\partial C}{\partial x}) + \frac{\partial}{\partial y}(D_R \frac{\partial C}{\partial y}) + \frac{\partial}{\partial z}(D_T \frac{\partial C}{\partial z}) \quad (1)$$

Where D_L, D_R and D_T are the principal diffusivities along the longitudinal, radial and tangential axes.

Initial and boundary conditions are:

$$t = 0 \qquad 0 < x < a \qquad 0 < y < b \quad 0 < z < c \qquad\qquad C = C(x, y, z, t) = 0 \quad (2)$$

$$t > 0 \quad x = 0 \quad x = a, y = 0 \quad y = b, z = 0 \quad z = c \quad C(x, y, z, t) = C_{eq} \quad (3)$$

- a, b, c are the sides of the parallelepiped.
- C (x, t): Is the concentration of liquid in the plate at time t and abscissa x.
- C_{eq}: Is the concentration obtained at equilibrium.

The kinetics of the transport of three-way material is obtained by making the product of the analytical solutions obtained for each direction of the transfer:

$$\frac{M_\infty - M_t}{M_\infty} = f(t, a).f(t, b).f(t, c) \quad (4)$$

$$\frac{M_\infty - M_t}{M_\infty} = \frac{512}{\pi^6} \cdot \sum_{i=0}^{i=\infty} \frac{1}{(2i+1)^2} \exp - [\frac{(2i+1)^2 \pi^2 D_L.t}{a^2}]$$

$$\times \sum_{j=0}^{j=\infty} \frac{1}{(2j+1)^2} \exp - [\frac{(2j+1)^2 \pi^2 D_R.t}{b^2}]$$

$$\times \sum_{k=0}^{k=\infty} \frac{1}{(2k+1)^2} \exp - [\frac{(2k+1)^2 \pi^2 D_T.t}{c^2}] \quad (5)$$

With a parallelepiped of sides are: a, b and c, and principal diffusivities are: D_L, D_R and D_T.

In the case of absorption, the amount of moisture transferred can also be expressed by the equation:

$$f(t, a) = 1 - \frac{2}{a} \sqrt{D_L \cdot t} \left[\pi^{\frac{-1}{2}} + 2.\sum_{n=1}^{n=\infty} (-1)^n \, ierfc \, \frac{nL}{(D_L \cdot t)^{\frac{1}{2}}} \right] \quad (6)$$

This equation being transformed for shorts times ($M_t/M_\infty < 0.5$) into the simple well-known equation:

$$\frac{M_t}{M_\infty} = \sqrt{t} \cdot \frac{2}{\sqrt{\pi}} \cdot \left(\frac{\sqrt{D_L}}{a} + \frac{\sqrt{D_R}}{b} + \frac{\sqrt{D_T}}{c} \right) \quad (7)$$
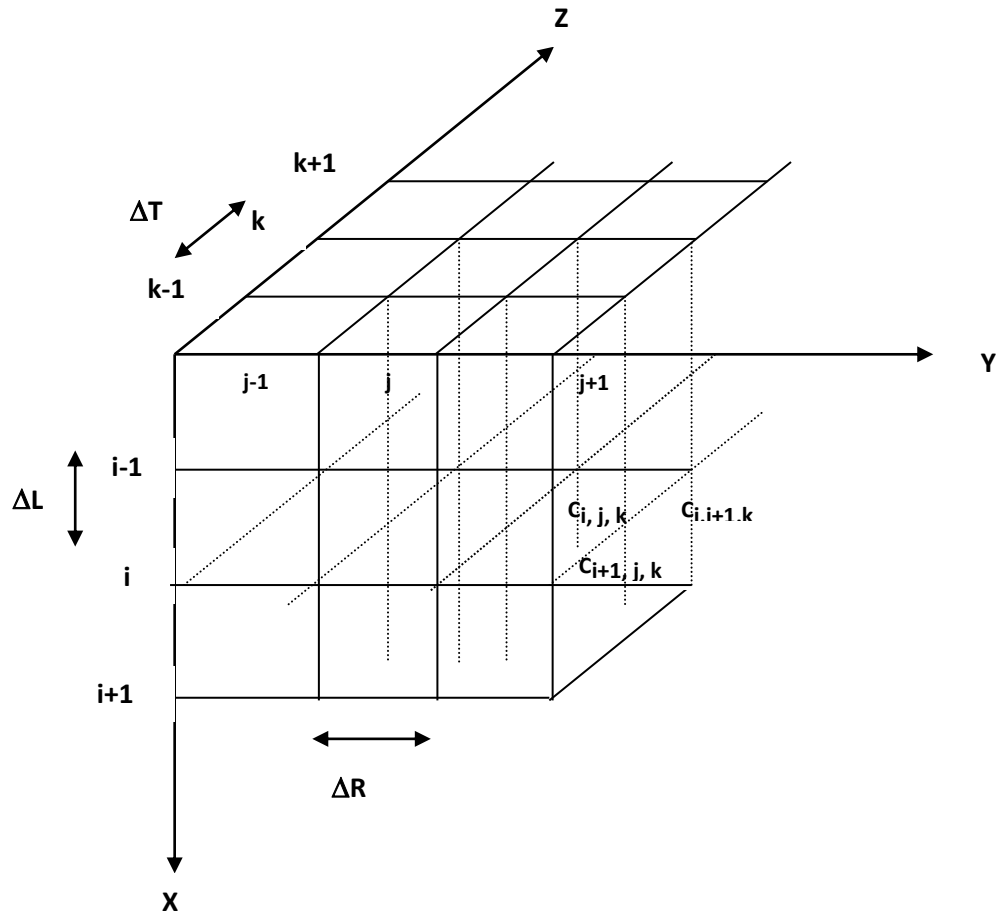
FIG. 1. **Diagram for numerical analysis.**

Numerical analysis

An explicit Numerical method with finite differences issued. Each dimension of the board is divided into equal finite slices of dimension ΔL, ΔT and ΔR and each position in wood is defined by three integers i, j, k such as:

$$X = i.\Delta L \qquad avec \qquad 0 < i < 2N_L \qquad L = 2N_L.\Delta L$$

$$Y = j.\Delta R \qquad avec \qquad 0 < J < 2N_R \qquad R = 2N_R.\Delta R \qquad\qquad (8)$$

$$Z = k.\Delta T \qquad avec \qquad 0 < K < 2N_T \qquad T = 2N_T.\Delta T$$

Time is divided into equal intervals Δt

Concentration within the wood

The water balance during the increment Δt is calculated within the small parallelepiped. of dimensions ΔL, ΔT and ΔR, by considering longitudinal, radial and tangential diffusion. The new concentration CNi, j, k at position i, j, k after step of time Δt is thus expressed in terms of previous concentrations C obtained at the same place and adjacent places for $1 \le I \le NL$, $1 \le J \le NR$ and $1 \le K \le NT$:

$$CN_{i,j,k} = C_{i,j,k} + \frac{1}{M_L}\left[C_{i-1,j,k} - 2C_{i,j,k} + C_{i+1,j,k}\right] + \frac{1}{M_T}\left[C_{i,j,k-1} - 2C_{i,j,k} + C_{i,j,k+1}\right]$$

$$+ \frac{1}{M_R}\left[C_{i,j-1,k} - 2C_{i,j,k} + C_{i,j+1,k}\right]$$

With the dimensionless numbers ML, MR and MT:

$$M_T = \frac{(\Delta T)^2}{\Delta t.D_T} \qquad M_R = \frac{(\Delta R)^2}{\Delta t.D_R} \qquad M_L = \frac{(\Delta L)^2}{\Delta t.D_L} \quad (10)$$

Concentration in surface:

$$C_S = C_\infty \quad (11)$$

Amount of water located in the sample

The amount of moisture located in the sample is calculated by integration the concentration with respect to space. Is used two auxiliary's variables V_A and V_B:

For $1 \leq I \leq N$ and $1 \leq j \leq N$:

$$V_A(i,j) = \frac{3}{4}C(i,j,0) + \frac{9}{4}C(i,j,1) + 2\sum_{k=1}^{N-1}C(i,j,k) + C(i,j,N)$$

For $1 \leq I \leq N$:

$$V_B(i) = \frac{3}{4}V_A(i,0) + \frac{9}{4}V_A(i,1) + 2\sum_{j=1}^{N-1}V_A(i,j) + V_A(i,N)$$

Finally:

$$M_t = \left(\frac{3}{4}V_B(0) + \frac{9}{4}V_B(1) + 2\sum_{j=1}^{N-1}V_B(j) + V_B(N)\right) \times (\Delta L.\Delta T.\Delta R) \quad (12)$$

Conditions of stability for calculation

In the right member of equation 12, the total coefficient for C (0,0,0) must ti be positive. The increment of time Δt must be chosen so that:

$$\frac{2}{M_L} + \frac{2}{M_T} + \frac{2}{M_R} + K.\Delta T.\left(\frac{2}{\Delta L} + \frac{2}{\Delta T} + \frac{2}{\Delta R}\right) \leq 1 \quad (13)$$

Experimental Procedure

Wood samples: Several samples of sapwood (pin maritine) are used in this study. They are cut in such way that their three axes are the same as the tree principal axes of diffusion. Various samples of wood are used either to the determination of principal diffusivities are displayed in TABLE 1.

TABLE 1. **The dimensions of the samples used.**

Sample 1	(L=2 cm, R= 0.5 cm, T= 2 cm)
Sample 2	(L=2 cm, R=1 cm, T= 2 cm)
Sample 3	(L=2 cm, R=2 cm, T=0.8 cm)

Experiments: The samples previously equilibrated in air at a RH a little 40%, are immersed in water at defined temperature. The process of absorption is followed by weighing the samples at intervals, until the weight remains constant.

Results and Discussion

The values obtained in this study for diffusivity are given in TABLE 2. These values of parameters DL, DR and DT, as well as the assumption of transient diffusion have been tested by considering a constant diffusivity with the help of analytical solutions and with the help of the numerical model. As shown in FIG. 1 good agreement is obtained between experiments and the values obtained by calculations. The numerical model describes the process of absorption during the whole process.

TABLE 2. **Values of parameters of diffusivity.**

Principal axis	Symbols	Diffusivity $^*10^5$ (cm^2/s)
Longitudinal	D_L	8
Radial	D_R	0.5
Tangential	D_T	0.4

In the other hand, the profiles of moisture content an easily calculated with numerical model. In spite of the fact that is difficult to determine how valid they are by experiment, these experiments being tedious and destructive. These profiles can give a good idea of the contribution of each transport (longitudinal, radial, tangential) at any place and time. Consequently, FIG. 2-4 show the analytical solutions of the kinetics of water absorption in the different samples sizes (1, 2 and 3), also FIG. 5 gives the graphical representation of the sample of the wood by description of profiles of moisture developed within the mid plane perpendicular to the longitudinal axis after 15 minutes of absorption.
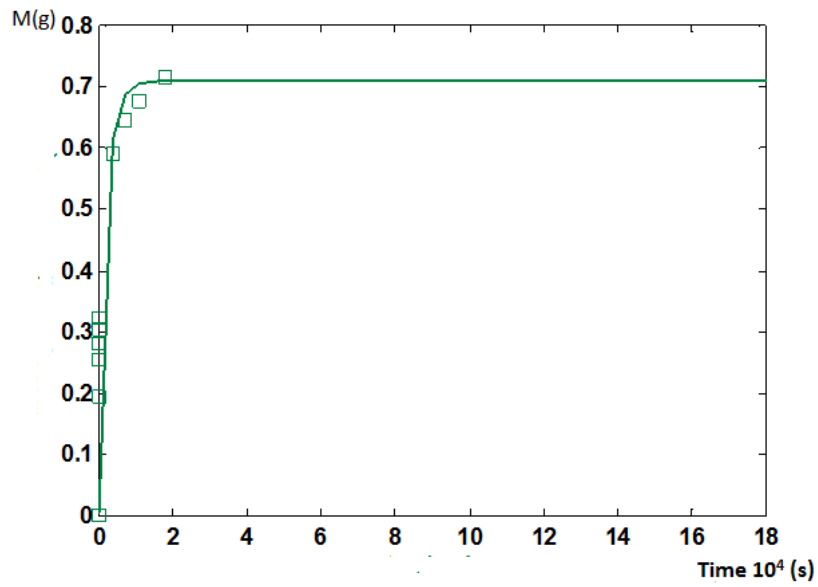
FIG. 2. Analytical solution for experiment of kinetic absorption of water through the tree directions at 30°C - Sample wood 1 (L=2 cm, R=0.5 cm, T=2 cm).
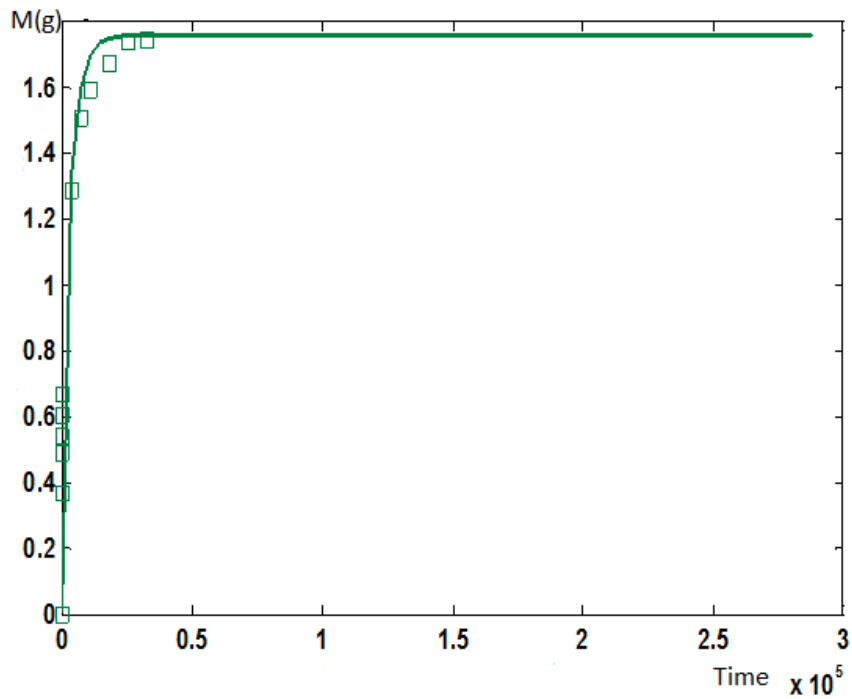

FIG. 3. Analytical solution for experiment of kinetic absorption of water through the tree directions at 30°C-Sample wood 2 (L=2 cm, R=1 cm, T=2 cm).
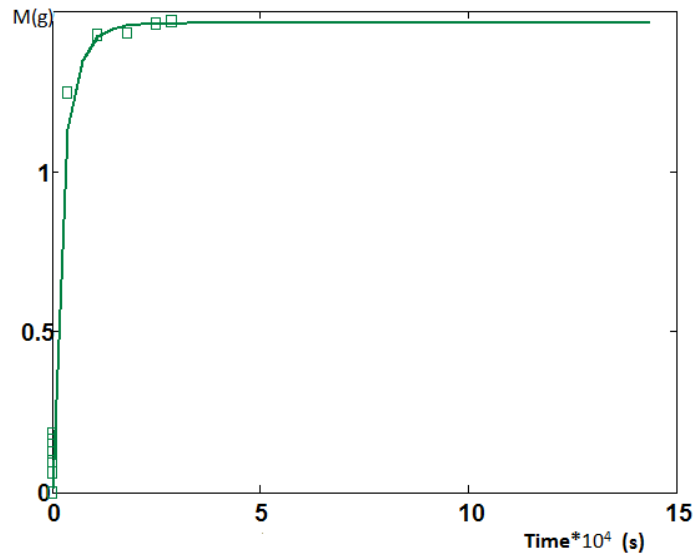
FIG. 4. **Analytical solution for experiment of kinetic absorption of water through the tree directions at 30°C - Sample wood 3 (L=2 cm, R=2 cm, T=0.8 cm).**
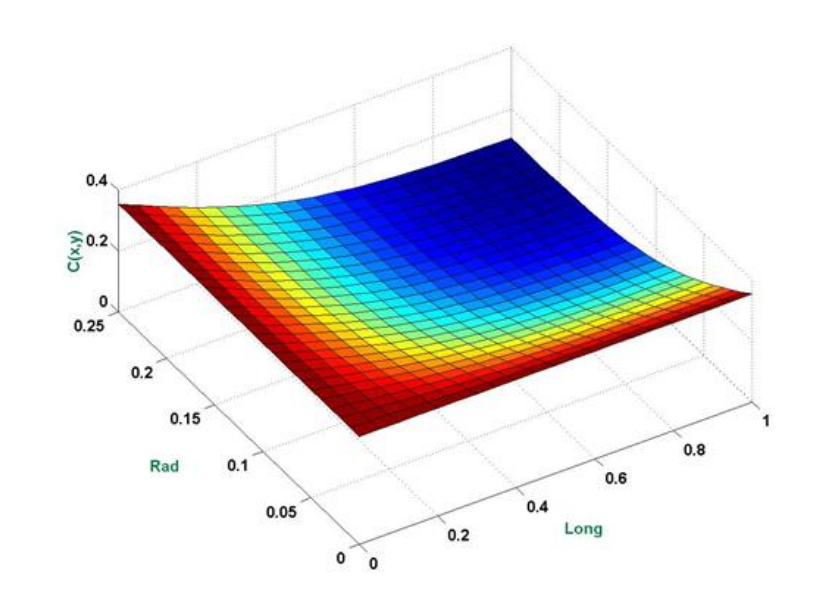

FIG. 5. **Profiles of Moisture developed within the mid plane perpendicular to the longitudinal axis after 15 minutes of absorption - Sample wood (L=2 cm, T=0.5 cm, R=2 cm) at T=30°C.**

Conclusion

The process of absorption of water is studied by considering the three-dimensional transfer with tree principal directions of diffusion. Numerical models with differences are able to describe the process of absorption under tree direction. The validity of these models is determined by comparing the theoretical kinetics of absorption with the experimental kinetic. The profiles of moisture content evaluated within the sample are able to gain a full model on the process.

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