Optimization of Heat and Mass Transfer in Capillary Porous Media during Drying Process

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Abstract: - A mathematical model was developed for optimization of heat and mass transfer in capillary porous media during drying process to predict the drying constants. The modeling equations verified the experimental results and proved to be an important tool in predicting the drying rate under different drying conditions.

Keywords: - Heat transfer, mass transfer, drying time, diffusion, moisture content, mathematical model.

1 Introduction

The importance of heat and mass transfer in capillary porous materials like wood has increased in the last few decades due to its wide industrial as well as research applications. In order to reduce moisture content in woods to a level low enough, to prevent undesirable biochemical reactions and microbiological growth, prolonged drying time and high temperature must often be used. In practice, several different techniques are used; natural drying, vacuum drying, convectional convective drying, high temperature convective drying, and more recently microwave drying [1].

Several physical mechanisms contribute to moisture migration during the process. For a porous solid matrix, with free water, bound water, vapor, and air, moisture transport through the matrix can be in the form of either diffusion or capillary flow driven by individual or combined effects of moisture, temperature and pressure gradients. The predominant mechanisms that control moisture transfer depend on the hygroscopic nature and properties of the materials, as well as the heating conditions and the way heat is supplied. In this regard, there is a need to assess the effects of the heat and mass transfer within the wood on the transfer in the fluid adjacent to it.

There are three stages of drying: In the first stage when both surface and core MC are greater than the FSP. Moisture movement is by capillary flow. Drying rate is evaporation controlled. In the second stage when surface MC is less than the FSP and core MC is greater than the FSP. Drying is by capillary flow in the core and by bound water diffusion near the surface as fiber saturation line recedes into wood, resistance to drying increases. Drying rate is controlled by bound water diffusion and finally in the third stage when both surface and core MC is less than the FSP. Drying is entirely by diffusion. As the MC gradient between surface and core becomes less, resistance to drying increases and drying rate decreases.

For wood, model developments have been based on either a mechanistic approach with the transfer phenomena derived from Fick's and Fourier's laws, or on the principles of thermodynamics and entropy production. These models may be divided into three categories: (a) diffusion models [2], (b) models based on transport properties [3,4] and (c) models based on both the transport properties and the physiological properties of wood related to drying [5,6].

Drying adds value to timber but also costs money. Working out the complete cost of drying is a complex process. Timber drying is a critical and costly part of timber processing. Comparing the cost and effectiveness of drying systems and technology is an important exercise, before drying systems are commissioned or are upgraded. Reduction in drying time and energy consumption offers the wood industries a great potential for economic benefit. But the reduction in drying time often results in an increase in drying related defects such as checks, splits and warp.

In previous work drying curves were fitted to four drying models and the goodness of fit of each model (Correlation Coefficient and Standard Error) was evaluated [7]. The main aim of this work is to find out a model for drying time and to predict the required time for drying samples to desired moisture content. In the second part the forecast time is compared with the theoretical approach. The predicted values by the theoretical model are compared with experimental data taken under actual drying conditions to demonstrate the efficiency of the predictive model.

2 Analytical Approaches

A software tool "Trend Analysis" for analysis the time series was applied. Trend analysis fits a general trend model to time series data and provides forecasts. S-curve is best fitted to our drying case. The S-curve model fits the Pearl-Reed logistic trend model. This accounts for the case where the series follows an S-shaped curve. The model is:

$$MC = \frac{10^a}{b_0 + b_1 b_2^t} \tag{1}$$

This tool is useful when we have dried the wood to moisture content not near to 30% and then predict the time needed to dry it completely.

Minitab computes three measures of accuracy of the fitted model: MAPE, MAD, and MSD for each of the simple forecasting and smoothing methods. For all three measures, the smaller the value, the better the fit of the model. These statistics are used to compare the fits of the different methods.

Mean Absolute Deviation (MAD) measures the accuracy of fitted time series values. It expresses accuracy in the same units as the data, which helps conceptualize the amount of error:

$$MAD = \frac{\sum_{t=1}^{n} \left| y_t - \hat{y}_t \right|}{n} \tag{2}$$

Where y_t equals the actual value at time $\hat{y}_t$ equals the fitted value, and n equals the number of observations.

Mean Absolute Percentage Error (MAPE) measures the accuracy of fitted time series values. It expresses accuracy as a percentage.

$$MAPE = \frac{\sum \left| \frac{(y_t - \hat{y}_t)}{y_t} \right|}{n} \times 100 \qquad (y_t \neq 0) \tag{3}$$

Where y_t equals the actual value at time $\hat{y}_t$ equals the fitted value, and n equals the number of observations.

MSD stands for Mean Squared Deviation. MSD is always computed using the same denominator, n, regardless of the model, so we can compare MSD values across models. MSD is a more sensitive measure of an unusually large forecast error than MAD.

$$MSD = \frac{\sum_{t=1}^{n} \left| y_t - \hat{y}_t \right|^2}{n} \tag{4}$$

Where y_t equals the actual value, t equals the forecast value, and n equals the number of forecasts.

3 Governing Equations

Heat and mass transfer in a body take place simultaneously during the drying process. The time required to go from an initial moisture content, U_0, to a certain value $\overline{U}$ is given in[8]:

$$t = \frac{1.6 \times 10^{-4} S_x^2 S_y^2}{\left(\mu_{x1}^2 D_x S_y^2 + \mu_{y1}^2 D_y S_x^2\right)} Log\left(\Gamma_{x1}\Gamma_{y1}\left(\frac{U_0 - U_{eq}}{\overline{U} - U_{eq}}\right)\right) \tag{5}$$

μ_{l1}^2 can be defined as:

$$\mu_{l1}^2 = \frac{1}{\frac{4}{\pi^2} + \frac{1}{B_l}} \tag{6}$$

Where B_l is the dimensionless constant called the "bio-criterion "of the sample:

$$B_l = \frac{\alpha_l R_l}{D_l} \tag{7}$$

Where R_l is half of the length of the rod, l is any of the two coordinates x,y, $S_x \times S_y$ is the width and thickness of sample, α_l is the coefficient of moisture exchange(m/s), D_l is the moisture diffusion coefficient(m^2/s) which can vary in each of the different directions for the wood sample.

The value Γ_{l1} is determined as:

$$\Gamma_{l1} = \frac{2B_l^2}{\mu_{l1}^2\left(B_l^2 + B_l + \mu_{l1}^2\right)} \tag{8}$$

and an average dimensionless moisture content $\overline{E}_\Sigma$ is:

$$\overline{E}_\Sigma = \frac{\overline{U} - U_{eq}}{U_0 - U_{eq}} \tag{9}$$

U_{eq} is the equilibrium moisture content of the wood.

Another theoretical approach is presented by [9]:

$$t = \frac{65S^2}{\overline{D}10^6}\left(1 + \frac{\pi^2 D}{2\alpha s}\right)\log\frac{U_0 - U_{eq}}{\overline{U} - U_{eq}} \tag{10}$$

Where $\overline{D}$ is the average diffusion coefficient and $\overline{S}$ is the average length of the dimensions of specimens.

4 Experimental data

Experimental material was obtained from two types of wood species, Guilan spruce and pine. The wood specimens were selected from Guilan region which is located in the north of Iran. The experiments were performed in a programmable domestic microwave drying system (Deawoo, KOC-1B4k) with a maximum power output of 1000 W at 2450MHz. Samples were dried in four methods: convection drying (150°C), microwave drying (270 W), infrared drying (100% power) and combination of microwave and convection drying. The dryer was run without the sample placed in, for about 30 min to set the desired drying conditions before each drying experiment. Throughout the experimental run the sample weights were continuously recorded at predetermined time intervals until wood reached to 30% of its moisture content.

5 Results and discussion

Figure 1-8 show the graphs moisture content variation against drying time, the model and the forecasted time for the four methods of drying on pine and Guilan spruce. Drying time is estimated to a moisture content of 14%. Results are relatively in a good agreement with drying curves. Just in some cases in heating up period this model didn't fit the experimental data closely. Heat is transferred by convection from heated air to the product to raise the temperatures of both the solid and moisture that is present. Moisture transfer occurs as the moisture travels to the evaporative surface of the product and then into the circulating air as water vapor. The heat and moisture transfer rates are therefore related to the velocity and temperature of the circulating drying air. Moreover, the momentum transfer may take place simultaneously coupled with heat and moisture transfer**.** Convective drying at intermediate temperatures has proved to be very effective from the economical point of view, thanks to the short drying time, the reduced sizes of the kilns, and the better control of the energy consumption and the possibility of a good integration in the production line.

Infrared energy is transferred from the heating element to the product surface without heating the surrounding air. When infrared radiation is used to heat or dry moist materials, the radiation impinges the exposed material, penetrates it and the energy of radiation converts into heat. Since the material is heated intensely, the temperature gradient in the material reduces within a short period the depth of penetration of radiation depends upon the property of the material and wavelength of radiation. Further by application of intermittent radiation, wherein the period of heating the material is followed by cooling, intense displacement of moisture from core towards surface can be achieved.

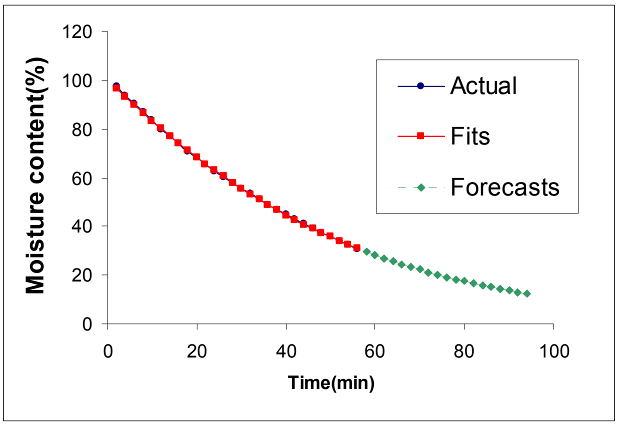

Fig.1.Moisture content vs. time for pine, (Convection drying**)**

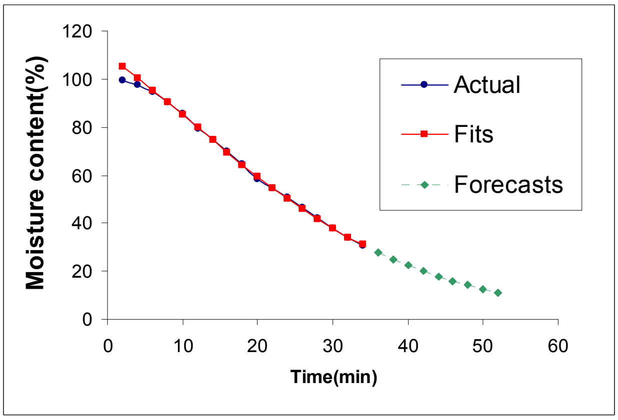

Fig.2.Moisture content vs. time for pine, (Infrared drying)

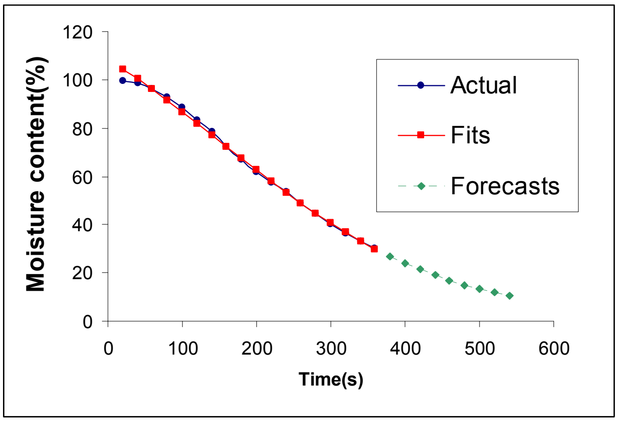

Fig.3.Moisture content vs. time for pine, (Microwave drying)

Microwave drying generate heat from within the grains by rapid movement of polar molecules causing molecular friction and help in faster and more uniform heating than does conventional heating. It should be pointed out that by variation of drying conditions (i.e. air temperature, humidity and air velocity) within a lumber stack, it is expected that the drying rate and the moisture content distribution varies as well [10].

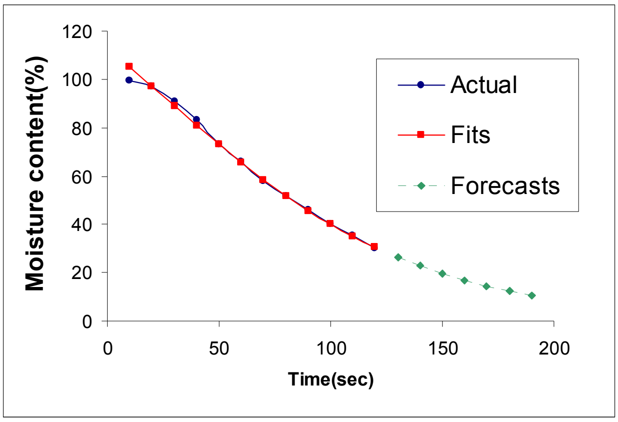

Fig.4.Moisture content vs. time for pine, (Combined dryer)

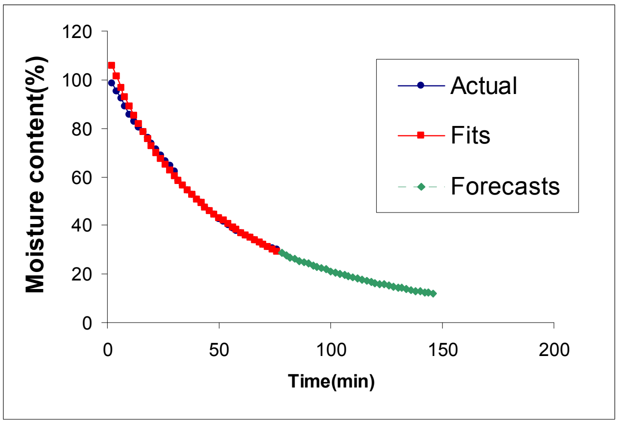

Fig. 5.Moisture content vs. time for spruce, (Convection drying)

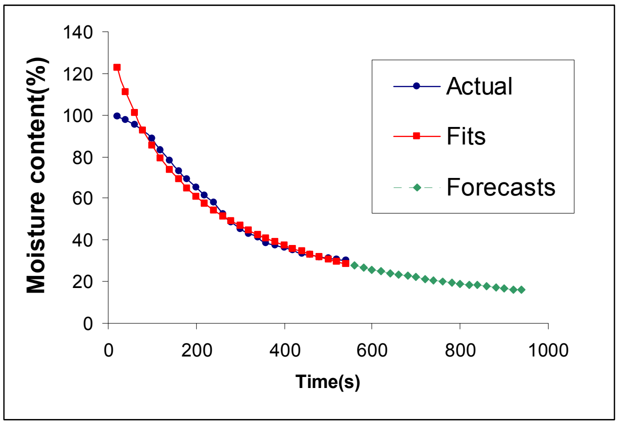

Fig.6.Moisture content vs. time for spruce (Microwave drying)

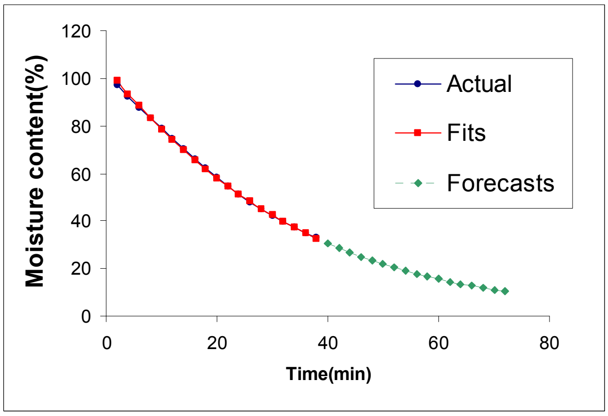

Fig.7.Moisture content vs. time for Spruce, (Infrared drying)

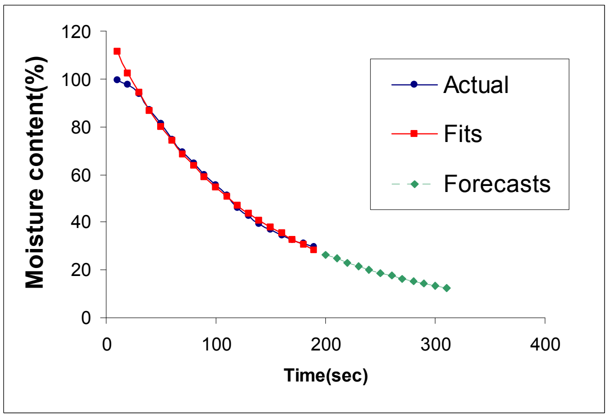

Fig.8.Moisture content vs. time for spruce, (Combined dryer)

The method of drying, type of samples, Mean Absolute Deviation, Mean Absolute Percentage Error, Mean Squared Deviation of these models used for moisture content change with time are presented in Table1.

Table1. Results of fitness

Type of Samples	Drying methods	MAPE	MAD	MSD
pine	Convection	0.341876	0.221418	0.080966
	Microwave	1.08315	0.86600	2.08191
	Infrared	1.07610	0.83372	2.51506
	Combined	1.26813	1.00335	3.72067
spruce	Convection	1.61692	1.16996	4.21973
	Microwave	4.8156	3.3411	33.2286
	Infrared	0.638023	0.420579	0.342695
	Combined	2.46335	1.63377	9.40387

It is clear that the MAPE, MAD, MSD values of this model were changed between 0.34-4.8, 0.22-1.63 and 0.08-33.22 respectively. As it can be seen for pine samples the convection method has a better fitness to the model and for spruce infrared drying model fitted the experimental data properly.

The estimated values are based on data from [11] and can be conveniently used for theoretical approach are shown in table 2.

It was assumed that the diffusion coefficient bellow FSP can be represented by [11]:

$$D = A.e^{\frac{-5280}{T}}.e^{\frac{Bu}{100}} \qquad (11)$$

Where T is the temperature in Kelvin, u is percent moisture content, A and B are experimentally determined.

Table2. Set of data selected for this study

Specifications	value	Reference
S_x	2.9cm	[11]
S_y	10.2cm	[11]
u_0	82.5%	[11]
u_{eq}	16.2%	[11]
$\overline{u}$	19%	[11]
T	316.15K	[11]
α	$0.787\times10^{-5} cm/s$	[11]
D	$8.711\times10^{-6} cm/s$	Equation(11)
β_x	1.3099	Equation(7)
β_y	4.6072	Equation(7)
μ_x	0.925	Equation(6)
μ_y	1.2676	Equation(6)
Γ_x	0.99	Equation(8)
Γ_y	0.985	Equation(8)
A	$11.7 cm^2/s$	[11]
B	$3.14 cm^2/s$	[11]
t	213hr	Equation(5)
t	557.32hr	Equation(10)
t	420hr	Trend analysis
t (real time)	550hr	[11]

Drying time is calculated from theoretical approach and evaluated model. Results show that real time had best agreement with which was obtained from equation (10) while there was a significant difference between real time and the one obtained from equation (5). Some authors have assumed that the diffusion coefficient depends strongly on moisture content [12-14] while others have taken the diffusion coefficient as constant [15-18]. Also, different boundary conditions have been assumed by different authors [19-22]. But Liu. et al concluded that the diffusion coefficient is a function of time, position, moisture content, and moisture gradient, which is at variance with assumptions in the literature that the diffusion coefficient is either a constant or a function of moisture content only [23].The difference in drying time may be due to the fact that diffusion coefficient was assumed to be the same in tangential and radial direction. So this assumption can't be used for equation (5). The same calculation can be done for other drying methods to predict the drying time.

6 Conclusions

Selection of the optimum operating conditions to obtain good quality dried products requires knowledge of the effect of the process parameters on the rate of internal-external mass transfer. High temperature heat treatment of wood is a complex process involving simultaneous heat, mass and momentum transfer phenomena and the effective models are necessary for process design, optimization, energy integration, and control.

Infrared heating offers many advantages over conventional drying under similar drying conditions. These results in high rate of heat transfer compared to conventional drying and the product is more uniformly heated rendering better quality characteristics. Microwave drying offers a number of advantages such as rapid heating, selective heating and self-limiting reactions which in turn can lead to improved quality and product properties, reduced processing time, and energy consumption and labor savings.

For pine samples the convection method has accurate result to the model and for spruce infrared drying model fitted the experimental data properly, thus their model was found to be adequate in predicting drying time of wood samples under different drying methods. The principle reason for drying wood at higher temperatures is because the rate of diffusion increases with the temperature. Water molecules generally diffuse from a region of high moisture content to a region of low moisture content, which reduces the moisture gradient and equalizes the moisture content. Diffusion plays an important role in the drying of lumber, at all moisture content with impermeable timbers and in permeable timber wherever the moisture content is too low for hydrodynamic flow of water through the lumens. Diffusion coefficient is influenced by the drying temperature, density and moisture content of timber. Other factors affecting the diffusion coefficient that are yet to be quantified are the species (specific gravity) and the growth ring orientation.

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