A study of heat and mass transfer during drying of wood with particular consideration on the physical parameters

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Abstract: - Economy and rapidity are common to the drying of wood products and in some cases these products should be dried under some specific conditions necessary to preserve their quality. In this paper, experiments conducted to evaluate the impact of different types of heat transfer mode on drying characteristics of wood. The results in the form of traditional rate of drying rates of drying curves are obtained and discussed with various internal and external physical parameters.

Keywords: Heat transfer, mass transfer, physical parameters, drying conditions, drying model, drying rate

1 Introduction

When a wet solid is subjected to thermal drying two processes occur simultaneously: First, transfer of heat to raise the wet solid temperature and evaporate the moisture content secondly, transfer of mass in the form of internal moisture to the surface of the solid and its subsequent evaporation. The rate at which drying is accomplished is governed by the rate at which these two processes proceed [1, 2]. In convective drying, heat transfer will occur through flow of heat. Mass transfer in the drying of solid will depend on two mechanisms: movement of moisture internally within the solid which will be a function of the internal physical nature of the solid and its moisture content; and the movement of water vapor from the material surface as a result of external conditions of temperature, air humidity and flow and area of exposed surface [3-5].

Moisture moves from an area of higher moisture content to an area of lower moisture content within the wood. When the surface moisture evaporates from the sides or ends, moisture moves from the interior toward these locations. As drying progresses, the supply of moisture can no longer keep pace with the rate of surface evaporation. Then, the internal transfer, characterized by the moisture diffusion (internal transfer) coefficient, controls the rate of drying. This process continues until the wood reaches its equilibrium moisture content with the ambient air conditions [6].The moisture in wood can be transported in three different ways. Firstly, above fiber saturation point, the free water is transported by means of capillary forces. Secondly, differences in vapor pressure give rise to convection or advection of moisture. Thirdly, differences in moisture content can cause diffusion of vapor [7]. In terms of drying rate and final moisture content distribution, the three factors believed to be important are board properties, drying schedules and drying condition variation within a kiln stack. The board properties include green moisture content, wood basic density, sapwood/heartwood mixture in a single board, board thickness variation and ring orientation pattern. Each of these variables can have a different level of influence on the drying rate and moisture content distribution [8].

The main aim of this project is to study the drying characteristics of wood. In the first part of this survey the results are presented in terms of classical theory of drying. The experimental data were fitted to four drying models. In the second part, the color development of wood after drying is examined using spectrophotometers. In the third part the effect of drying temperature and drying modes on the hardness and surface roughness of wood samples are evaluated.

2 Governing Equations

For the microwave drying process at an initial mass, temperature and moisture content of (m_0, T_0, U_0)

respectively, the time required for initial heating up period is:

$$t_i = \left[\frac{\overline{P}}{V}\right]^{-1} h(100 - T_0)\rho \qquad (1)$$

Where $\left(\frac{\overline{P}}{V}\right)$ represents the average power absorbed per unit volume, (ρ) is the density of the material, (h) is the specific heat of the material.

After heating up stage and when the material reaches 100°C, a constant drying period will appear, and the water will start to evaporate from the surface at a constant rate. In this stage, at steady state conditions the average power absorbed by the material is totally balanced by the latent heat of water (λ) as follows:

$$\Delta m = -\frac{1}{\lambda}\left[\frac{\overline{P}}{V}\right].V.\Delta t.m_0 \qquad (2)$$

Where (V) is the volume of the material, (Δm) is the mass of the water evaporated during the time (Δt). At a critical point, when all moisture has evaporated from the surface, moisture from the inner part of the material will be forced to move to the surface and the falling drying period will start.

The average power absorbed per unit volume $\left(\frac{\overline{P}}{V}\right)$ can be calculated using the following expression:

$$\frac{\overline{P}}{V} = \varepsilon'\varepsilon_0 E_i^2 \tan\delta.2\pi f \qquad (3)$$

Where E_i is the electric field strength inside the material, ε' is the dielectric constant of the material, ε_0 is the permittivity of vacuum $\left(= 8.854*10^{-12} Fm^{-1}\right)$, ε'' is the dielectric loss factor and $\tan\delta$ is defined:

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} \qquad (4)$$

The values of E_i, ε', ε'' at a particular time are determined in [9]. Meanwhile, heat and mass transfer in a body take place simultaneously in three directions 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[10]:

$$t = \frac{R_x^2 R_y^2 R_z^2}{\mu_{x1}^2 D_x R_y^2 R_z^2 + \mu_{y1}^2 D_y R_x^2 R_z^2 + \mu_{z1}^2 D_z R_x^2 R_y^2} Ln \frac{\Gamma_{x1}\Gamma_{y1}\Gamma_{z1}}{\overline{E}_\Sigma} \qquad (5)$$

Where R_l is half of the length of the rod, l is any of the three coordinates x,y, or z.

μ_{l1}^2 can be defined as:

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

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

$$B_l = \frac{\alpha_l R_l}{D_l} \qquad (7)$$

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:

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

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

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

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

3 Experimental

Two types of wood samples (namely; Guilan spruce and pine) were selected for our drying investigation. The wood specimens were selected from Guilan region which is located in the north of Iran. To establish the impact of each type of heat transfer mode on drying characteristics of wood and compare it with numerical solutions 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. In convection drying the air circulates around the sample with a speed of 1 m/s and the air temperature in the range of 55-250°C. The dryer was run without the sample placed in, for about 30 min to set the desired drying conditions before each drying experiment. All wood samples were dried to a moisture content of approximately 30%. At 1 minute interval throughout the drying process (until wood reached to 30% of its moisture content) the specimens were removed, weighted and then replaced to measure their moisture content.

After drying, each sample was tested for hardness using the Brinell hardness method. The force ranges while applying parallel to the grain was in the order of 1000-1900 N. In the case of perpendicular to the grain the force variation was in the ranges of 750-1400 N.

Color change measurements were made both on fresh and dried boards and always from the freshly planed surface. The spectrum of reflected light in the visible region (400-750 nm) was measured and transformed to the CIEL*a*b* color scale using a 10º standard observer and D65 standard illuminant. These color space values were used to calculate the total color change (ΔE^*) applied to samples according to the following equation:

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (10)$$

The average roughness is the area between the roughness profile and its mean line, or the integral of the absolute value of the roughness profile height over the evaluation length:

$$R_a = \frac{1}{L}\int_0^L |r(x)dx| \quad (11)$$

When evaluated from digital data, the integral is normally approximated by a trapezoidal rule:

$$R_a = \frac{1}{N}\sum_{n=1}^{N}|r_n| \quad (12)$$

The root-mean-square (rms) average roughness of a surface is calculated from another integral of the roughness profile:

$$R_q = \sqrt{\frac{1}{L}\int_0^L r^2(x)dx} \quad (13)$$

The digital equivalent normally used is:

$$R_q = \sqrt{\frac{1}{N}\sum_{n=1}^{N} r_n^2} \quad (14)$$

R_z (ISO) is a parameter that averages the height of the five highest peaks plus the depth of the five deepest valleys over the evaluation length.

These parameters which are characterized by ISO were employed to evaluate influence of drying methods on the surface roughness of the samples.

4 Analytical Approaches

Drying curves were fitted with four drying models, namely, the Newton, the Henderson and Pabis, the Logarithmic and the Wang and Singh models (Table1). The moisture ratio of wood samples during drying experiments was calculated using the following equation:

$$MR = \frac{M - M_e}{M_0 - M_e} \quad (15)$$

Where, MR, M, M_0, M_e are the moisture ratio, moisture content (kg water/kg dry matter) at any time, initial moisture content and equilibrium moisture content respectively.

The regression was performed in Labfit computer program. Two criteria were adopted to evaluate the goodness of fit of each model, the Correlation Coefficient (r) and the Standard Error (S).

The standard error of the estimate is defined as follows:

$$S = \sqrt{\frac{\sum_{i=1}^{N}(MR_{\exp,i} - MR_{\mathrm{Pred},i})^2}{N-n}} \quad (16)$$

Where $MR_{\exp,i}$ is the experimental moisture ratio at observation i; $MR_{\mathrm{Pred},i}$ is the predicted moisture ratio at observation i; N is the number of observation; n is the number of constants.

Table1. Mathematical models for drying curves

Model equations	Model name	References
$MR = \exp(-at)$	Newton	[11]
$MR = a\exp(-bt)$	Henderson and Pabis	[12]
$MR = a\exp(-bt) + c$	Logarithmic	[13]
$MR = 1 + at + bt^2$	Wang and Singh	[14]

To explain the meaning of correlation coefficient, we must define some terms used as follow:

$$S_t = \sum_{i=1}^{N}(\bar{y} - MR_{\exp,i})^2 \quad (17)$$

Where, the average of the data points ($\bar{y}$) is simply given by:

$$\bar{y} = \frac{1}{N}\sum_{i=1}^{N} MR_{\exp,i} \quad (18)$$

We also define the deviation from the fitting curve as:

$$S_r = \sum_{i=1}^{N}(MR_{\exp,i} - MR_{pred,i})^2 \quad (19)$$

In view of the above, the improvement (or error reduction) due to describing the data in terms of a regression model can be quantified by subtracting the two quantities. Because the magnitude of the quantity is dependent on the scale of the data, this difference is normalized to yield:

$$r = \sqrt{\frac{S_t - S_r}{S_t}} \quad (20)$$

Where, *r* is defined as the correlation coefficient. As the regression model better describes the data, the correlation coefficient will approach unity. For a perfect fit, the standard error of the estimate will approach *S*=0 and the correlation coefficient will approach *r*=1.

5 Results and Discussion

Figure 1 shows the graphs of moisture content variation against drying time for infrared and convection drying and figure 2 is for microwave and combined drying on pine and Guilan spruce. It can be obviously observed that the values of moisture content for pine is rather more than the values for Guilan spruce and it reaches to the same moisture content later than pine samples. In view of the above, it can be noted that board properties are important factor on drying rate.

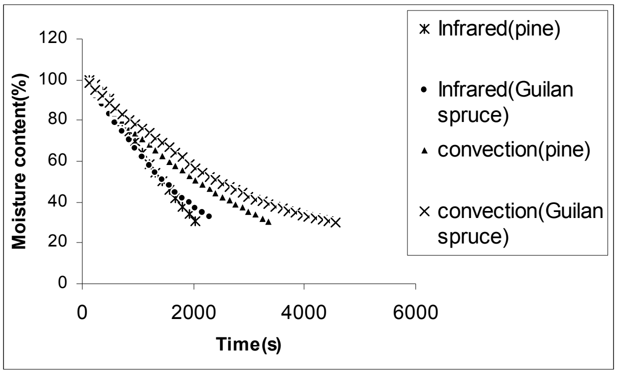

Fig. 1.Moisture content vs.time

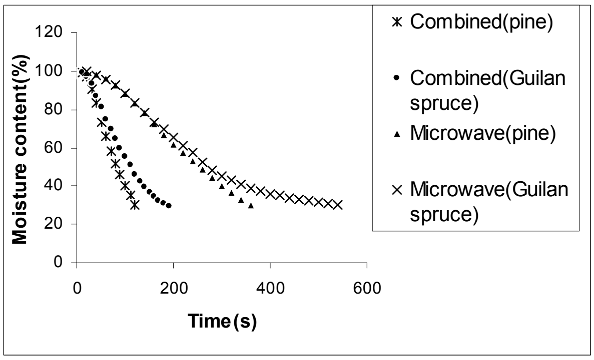

Fig.2. Moisture content vs. time

From figures 1 and 2 a significant improvement in drying time can be observed. Such a time reduction can be noted while using convective drying in contrast, figure 2 illustrates the significant reduction in drying duration. .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.

The values of hardness are shown in figure3. In both type of samples the hardness measured in longitudinal direction is reported to be higher than tangential. The amount of fibers and its stiffness carrying the load are expected to be lower when the load direction is angled to the grain. Hardness of wood increased in combined drying. The hardness of wood is proportional to its density. The hardness of wood varies, depending on the position of the measurement. Late-wood is harder than early wood and the lower part of a stem is harder than the upper part. Increase in moisture content decreases the hardness of wood.

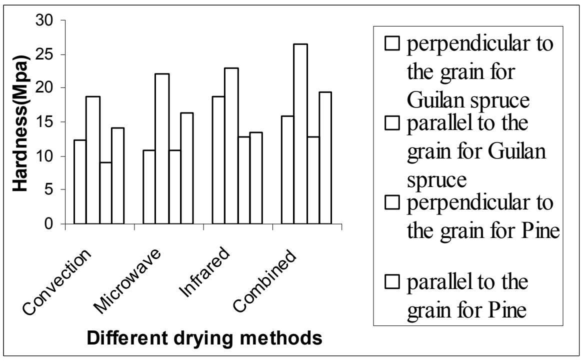

Fig.3. Brinell hardness

Color changes of pine and Guilan spruce samples were shown in figure4 and 5, respectively. Results show that the lightness values ΔL^* increased during drying. The L^* of wood species such as tropical woods which originally have dark color increases by exposure to light. This is due to the special species and climate condition of Guilan spruce and pine wood samples. Positive values of Δb^* indicate an increment of yellow color and negative values an increase of blue color. Negative values of Δa^* indicate a tendency of wood surface to greenish. A low ΔE^* corresponds to a low color change or a stable color. The biggest changes in color appeared in ΔE^* values of pine samples during infrared drying while for Guilan spruce it was reversed. Due to differences in composition of wood components, the color of fresh, untreated wood varies between different species, between different trees of the same species and even within a tree. Within a species wood color can vary due to the genetic factors, and environmental conditions. Discolorations caused by the drying process are those which actually occur during drying and are mainly caused by non-microbial factors. Many environmental factors such as solar radiation, moisture and temperature cause weathering or oxidative degradation of wooden products during their normal use; these ambient phenomena can eventually change the chemical, physical, optical and mechanical properties of wood surfaces.

Table 2 and Table 3 displays the changes in surface roughness parameters (R_a , R_z and R_q) of the Pine and Guilan spruce at varying drying methods. In both cases the surface roughness became higher during microwave and infrared heating while surface smoothness of both pine and Guilan spruce increased during convection and

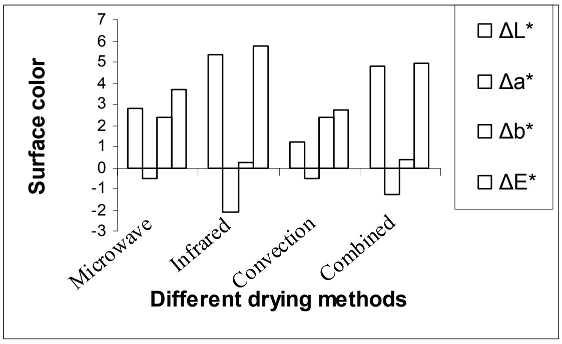

Fig.4. Surface color development of Pine

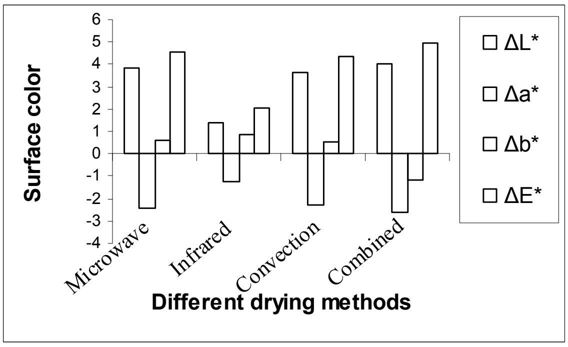

Fig.5.Surface color development of Guilan spruce

Table2.surface roughness (μm) for pine

Drying methods	Drying conditions	R_a	R_z	R_q
Microwave	Before drying	4.52	24.68	5.39
	After drying	5.46	30.21	6.62
Infrared	Before drying	4.42	25.52	5.43
	After drying	4.87	26.55	5.69
Convection	Before drying	4.66	26.87	5.86
	After drying	4.08	24.64	5.12
Combined	Before drying	5.23	32.59	6.42
	After drying	3.41	21.7	4.27

Table 3.surface roughness (μm) for Guilan spruce

Drying methods	Drying conditions	R_a	R_z	R_q
Microwave	Before drying	6.44	34.18	7.85
	After drying	7.77	44.3	9.82
Infrared	Before drying	4.92	30.61	6.30
	After drying	6.42	38.93	8.17
Convection	Before drying	4.97	32.41	6.5
	After drying	4.78	32.27	6.34
Combined	Before drying	10.41	59.5	13.37
	After drying	9.11	54.31	11.5

combined drying. However, the roughness of wood is a complex phenomenon because wood is an anisotropic and heterogeneous material. Several factors such as anatomical differences, growing characteristics, machining properties of wood, pretreatments (e.g. steaming, drying, etc.) applied to wood before machining should be considered for the evaluation of the surface roughness of wood.

Table4. Results of modeling

Models	Constants	r	s
Newton	1) a = 0.012311	0.9135	0.135
	2) a = 0.0103481	0.942	0.1149
	3) a = 0.000572	0.971	0.0709
	4) a = 0.0004903	0.975	0.067
	5) a = 0.0007559	0.9219	0.1305
	6) a = 0.0008133	0.9573	0.0897
	7) a = 0.004203	0.912	0.1409
	8) a = 0.004173	0.94705	0.1101
Henderson and Pabis	1) a = 1.3376 b = 0.0173625	0.9708	0.0839
	2) a = 1.30317 b = 0.0134948	0.9784	0.0728
	3) a = 1.16522 b = 0.0006773	0.992	0.033
	4) a = 1.15555 b = 0.0005689	0.987	0.0479
	5) a = 1.2928 b = 0.00100667	0.9651	0.091
	6) a = 1.2219 b=0.00101251	0.9831	0.05846
	7) a = 1.30713 b=0.00566565	0.959	0.0998
	8) a = 1.28789 b = 0.00533431	0.978	0.071
Logarithmic	1) a = 6.0309 b = 0.0018449 c = -4.8706	0.9964	0.031
	2) a = 1.793 b = 0.0058224 c = -0.62868	0.9971	0.0273
	3) a = 1.7103 b = 0.00028705 c = -0.64877	0.999	0.0021
	4) a = 1.4464 b = 0.00030291 c = -0.38344	0.999	0.011
	5) a = 10.024 b = 0.000058979 c = -8.907	0.998	0.0215
	6) a = 1.9971 b = 0.00035778 c = -0.90351	0.999	0.00693
	7) a = 72.712 b = 0.000044397 c = -71.585	0.996	0.0285
	8) a = 1.5642 b = 0.0028875 c = -0.38822	0.999	0.0114
Wang and Singh	1) a = -0.005561 b = -0.00003064	0.9865	0.0571
	2) a = -0.006556 b = 0.000005096	0.987	0.0544
	3) a = -0.000395 b = 0.0000000282	0.998	0.017
	4) a = -0.0003498 b = 0.00000002782	0.998	0.0171
	5) a = -0.0003682 b=0.00000007161	0.9925	0.0424
	6) a = -0.0005274 b = 0.000000028	0.9961	0.0281
	7) a= -0.001879 b = -0.000003003	0.9906	0.0485
	8) a = -0.002838 b = 0.00000156	0.9845	0.061

The model equations, method of drying, type of samples, model constants, standard error and correlation coefficient of these models used for moisture ratio change with time are presented in Table4. In this table 1 represents Combined Pine,2 Combined Guilan Spruce,3 Convection Pine,4 Convection Guilan Spruce ,5 Infrared Pine,6 Infrared Guilan Spruce,7 Microwave Pine and 8 Microwave Guilan Spruce respectively. All the models gave consistently good correlation coefficient values in the range of 0.912-0.999.

This indicates that all models could satisfactorily describe the air-drying of wood samples. Among the drying models, the Logarithmic model obtained the highest r values and the lowest s in the different drying methods of the study. It is clear that the r and s values of this model were changed between 0.996 and 0.999, 0.0021 and 0.0285, respectively. Thus, this model may be assumed to present the drying behavior of wood samples.

6 Conclusion

From this study, it will be clear that there are a lot of factors that have to be considered before employing microwave irradiation for wood drying. Blind applications of microwave energy in wood industry will usually lead to disappointment. In general, the savings achieved through microwave processing will be other than energy as the saving in this respect would not be enormous. The benefits will be in time saving, increased process yield, environmental compatibility, space saving and unique characteristics of the products. For Guilan spruce the average of hardness is shown to be much higher than pine. From the experimental results it can be observed that in combined microwave dryer, the drying time is significantly reduced while the hardness were relatively improved in comparison to the other drying methods. Microwave and infrared drying can increase wood surface roughness while the smoothness of wood increases during convection and combined drying. The effect varies with the wood species. Thus this work suggests keeping the core temperature below the critical value until the wood has dried below fiber saturation as one way of ensuring that the dried wood is acceptably bright and light in color.

Logarithmic model had a high correlation coefficient and low Standard errors and thus was found to be adequate in describing the drying behavior of wood samples under different drying methods.

Challenges remain to be overcome through a fundamental understanding of microwave interaction with wood, innovations, R&D investigations and advanced engineering, especially in designing efficient process control devices.

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