

Experimental Survey on Microwave Drying of Porous Media

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ABSTRACT: *The cost of drying carpet which is done toward the end of the manufacturing process, is quite high. The carpet industry has been using convection drying for many years. Little attention has been given to quantifying the effect of microwave power during the drying of carpet. An experimental system was developed whereby air was introduced into the cavity of a domestic microwave oven. The results indicated that microwave power levels and sample specifications are the most important parameters, with statistically significant effects on the drying constants.*

KEY WORDS: *Microwave drying, Moisture content, Porous media, Tufted textile.*

INTRODUCTION

A very common method of removing water from textiles is convective drying. Hot air is used as the heat transfer medium and is exhausted to remove vaporized water. The effect of humidity ratio on drying rates has been studied for many materials, but textile products have seldom been the subject. The results of these studies indicate that the effect of humidity depends strongly on the temperature of the drying medium.

Carpet manufacturing involves a crucial energy-intensive drying stage at the end of the process to remove the moisture left from dye setting. Determining drying characteristics for carpet tiles is vitally important so as to optimize this drying stage. After the undyed carpet tile is manufactured, it is subject to a dyeing and steaming process, which results in substantial condensation of water on the tile's surface. Most of the moisture is removed by mechanical means, but the rest must be

removed by drying the tiles in a dryer. There are two possible outcomes: one is that the tile can be over dried, running the risk of warping the materials, or two, there may still be moisture inside. The latter outcome is obviously a problem when the residual moisture evaporates and the carpet fibers shrink, causing the tile curl and lift from the floor at opposite corners.

While cost represent a major barrier to wider use of microwaves in industry, an equally important barrier is the lack of understanding of how microwaves interact with materials during heating and drying. One of the main features which distinguished microwave drying from conventional drying process is that because liquids such as water absorb the bulk of the electromagnetic energy at microwave frequencies, the energy is transmitted directly to the wet material. The process does not rely on conduction of heat from the surface of the

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product and thus increased heat transfer occurs, speeding up the drying process. This has the advantage of eliminating case hardening of products which is usually associated with convective hot air drying operations.

Quantitative information regarding the microwave-material interaction can be deduced by measuring the dielectric properties of the material, in particular of the real and imaginary part of the relative complex permittivity, $\epsilon = \epsilon' - j\epsilon''_{\text{eff}}$, where the term ϵ''_{eff} includes conduction losses, as well as dielectric losses. The relative permittivity is not a constant and strictly depends on frequency and temperature. A different and more practical way to express the degree of interaction between microwaves and materials is given by two parameters: the power penetration depth (D_p) and the power density dissipated in the material (P), defined in a simplified version as follows:

$$D_p = (\lambda_0 \sqrt{\epsilon''}) / 2\pi\epsilon''$$

$$P = 2\pi f \epsilon_0 \epsilon''_{\text{eff}} E_{\text{rms}}^2$$

where $\epsilon = \epsilon' - j\epsilon''_{\text{eff}}$ is the complex permittivity of the material under treatment, λ_0 is the wavelength of the radiation, f is its frequency, $\epsilon_0 = (8,854)10^{-12}$ F/m is the permittivity of empty space and E_{rms} is the electric field strength inside the material itself. P and D_p can only give qualitative and often misleading information, especially when it is critical to determine the temperature profiles inside the material. Others are the variables involved, however from these two parameters can be deduced most of the peculiarities which make the microwave heating a unique process.

Background

Since world war II, there have been major developments in the use of microwaves for heating applications. After this time it was realized that microwaves had the potential to provide rapid, energy-efficient heating of materials. The main applications of microwave heating today include food processing, wood drying, plastic and rubber treating as well as curing and preheating of ceramics. Broadly speaking, microwave radiation is the term associated with any electromagnetic radiation in the microwave frequency range of 300 MHz-300 GHz. Domestic and industrial microwave ovens generally operate at a frequency of 2.45 GHz

corresponding to a wavelength of 12.2 cm. However, not all materials can be heated rapidly by microwaves. Materials may be classified into three groups, *i.e.* conductors, insulators and absorbers. Materials that absorb microwave radiation are called dielectrics, thus, microwave heating is also referred to as dielectric heating. Dielectrics have two important properties:

- They have very few charge carriers. When an external electric field is applied there is very little change carried through the material matrix.

- The molecules or atoms comprising the dielectric exhibit a dipole movement distance. An example of this is the stereochemistry of covalent bonds in a water molecule, giving the water molecule a dipole movement. Water is the typical case of non-symmetric molecule. Dipoles may be a natural feature of the dielectric or they may be induced. Distortion of the electron cloud around non-polar molecules or atoms through the presence of an external electric field can induce a temporary dipole movement. This movement generates friction inside the dielectric and the energy is dissipated subsequently as heat.

The interaction of dielectric materials with electromagnetic radiation in the microwave range results in energy absorbance. The ability of a material to absorb energy while in a microwave cavity is related to the loss tangent of the material.

This depends on the relaxation times of the molecules in the material, which, in turn, depends on the nature of the functional groups and the volume of the molecules. Generally, the dielectric properties of a material are related to temperature, moisture content, density and material geometry.

An important characteristic of microwave heating is the phenomenon of "hot spot" formation, whereby regions of very high temperature form due to non-uniform heating. This thermal instability arises because of the non-linear dependence of the electromagnetic and thermal properties of material on temperature. The formation of standing waves within the microwave cavity results in some regions being exposed to higher energy than others. This results in an increased rate of heating in these higher energy areas due to the non-linear dependence. Cavity design is an important factor in the control, or the utilization of this "hot spots" phenomenon.

Microwave energy is extremely efficient in the

selective heating of materials as no energy is wasted in "bulk heating" the sample. This is a clear advantage that microwave heating has over conventional methods. Microwave heating processes are currently undergoing investigation for application in a number of fields where the advantages of microwave energy may lead to significant savings in energy consumption, process time and environmental remediation.

Compared with conventional heating techniques, microwave heating has the following additional advantages:

- higher heating rates;
- no direct contact between the heating source and the heated material;
- selective heating may be achieved;
- greater control of the heating or drying process;
- reduced equipment size and waste.

LITERATURE

King and Cassie [1] conducted an experimental study on the rate of absorption of water vapor by wool fibers. They observed that, if a textile is immersed in a humid atmosphere, the time required for the fibers to come to equilibrium with this atmosphere is negligible compared with the time required for the dissipation of heat generated or absorbed when the regain changes. McMahon and Watt [2] investigated the effects of heat of sorption in the wool-water sorption system. They observed that the equilibrium value of the water content was directly determined by the humidity but that the rate of absorption and desorption decreased as the heat-transfer efficiency decreased. Heat transfer was influenced by the mass of the sample, the packing density of the fiber assembly, and the geometry of the constituent fibers. Crank [3] pointed out that the water-vapor-uptake rate of wool is reduced by a rise in temperature that is due to the heat of sorption. The dynamic-water-vapor-sorption behavior of fabrics in the transient state will therefore not be the same as that of single fibers owing to the heat of sorption and the process to dissipate the heat released or absorbed.

In order to model the two-stage sorption process of wool fibers, David and Nordon [4] proposed three empirical expressions for a description of the dynamic relationship between fiber moisture content and the surrounding relative humidity.

Wehner *et al* [5] presented two mechanical models to simulate the interaction between moisture sorption by fibers and moisture flux through the void spaces of a fabric. In the first model, diffusion within the fiber was considered to be so rapid that the fiber moisture content was always in equilibrium with the adjacent air. In the second model, the sorption kinetics of the fiber were assumed to follow Fickian diffusion. In these models, the effect of heat of sorption and the complicated sorption behavior of the fibers were neglected.

Li and Holcombe [6] developed a two-stage model, which takes into account water-vapor-sorption kinetics of wool fibers and can be used to describe the coupled heat and moisture transfer in wool fabrics. The predictions from the model showed good agreement with experimental observations obtained from a sorption-cell experiment. More recently, Li and Luo [7] further improved the method of mathematical simulation of the coupled diffusion of the moisture and heat in wool fabric by using a direct numerical solution of the moisture-diffusion equation in the fibers with two sets of variable diffusion coefficients. These research publications were focused on fabrics made from one type of fiber. The features and differences in the physical mechanisms of coupled moisture and heat diffusion into fabrics made from different fibers have not been systematically investigated. The current work on the use of the microwave is a development arising from previous studies [8-12].

THEORY

The conservation of mass and energy for the material give the following equations:

$$\frac{\partial X}{\partial t} = D_n \nabla^2 X \quad (1)$$

$$C_{pn} \rho_n \frac{\partial T}{\partial t} = \nabla (K_n \nabla T_m) + Q(r, z, t) \quad (2)$$

where $n = 1$ and 2 refers to the inner and outer layer of material, and D is diffusivity (m^2/s); X the moisture content (kg/kg dry basis); k the thermal conductivity ($W/m K$); ρ the density (kg/m^3); C_p the heat capacity ($J/kg K$); and Q is the microwave source term (W/m^3).

The empirical model for calculating moisture diffusivity as a function of moisture and temperature used for this study is;

$$D = \frac{1}{1+X} D_0 \exp \left[-\frac{E_0}{R} \left(\frac{1}{T_m} - \frac{1}{T_r} \right) \right] + \frac{1}{1+X} D_i \exp \left[-\frac{E_i}{R} \left(\frac{1}{T_m} - \frac{1}{T_r} \right) \right] \quad (3)$$

where D (m^2/s) is the moisture diffusivity; X the moisture content (kg/kg dry basis); T_m ($^{\circ}C$) the material temperature; $T_r = 60$ $^{\circ}C$ a reference temperature, and $R = 0.0083143$ kJ/mol K is the ideal gas constant; D_0 (m^2/s) the diffusivity at moisture $X = 0$ and temperature $T = T_r$; D_i (m^2/s) the diffusivity at moisture $X = \infty$ and temperature $T_m = T_r$; E_0 (kJ/mol) the activation energy of diffusion in dry material at $X = 0$ and E_i (kJ/mol) is the activation energy of diffusion in wet material at $X = \infty$. The proposed model uses the estimated parameters in Table 1.

Initial conditions: At time $t = 0$: $T_m = T_0(r, z)$, $X = X_0(r, z)$

- Boundary conditions:

$$\left. \frac{\partial X}{\partial t} \right|_{(r=0, H/2=0, t)} = 0,$$

$$\left. \frac{\partial T}{\partial t} \right|_{(r=0, H/2=0, t)} = 0$$

MATERIALS AND METHODS

The porous medium studied was unbacked cut-pile carpet. Unbacked tufted carpet consists primarily of short lengths of yarn, typically 5-20 mm long. These yarns, referred to as face yarn, are held in position by a very thin woven fabric, called primary backing. The face yarns are packed nearly parallel to each other and run perpendicular to the primary backing. The combined microwave and air dryer consists essentially a duct with a fan, heating section and microwave oven cavity functioning as a drying chamber. Ambient air was drawn through the duct assembly to the drying chamber by centrifugal fan located at the end of the duct. The air was then passed through an electric heating element and was mixed in the reduction section before being introduced to the cavity. The fan is powered by a variable speed controller. The heater has a rated capacity of 1 Kw and is connected to a voltage controller to achieve the desired dry bulb temperature in the range of 30-70 $^{\circ}C$.

The temperatures was continuously monitored using a type-K thermocouple. The air velocity and humidity were

Table 1: Numerical values *

Diffusion coefficient of water vapor - 1st stage :
$(1.04 + 68.20 W_c - 134259 W_c^2) 10^{-14}$, $t < 540s$
Diffusion coefficient of water vapor - 2nd stage :
$1.6164 \{1 - \exp[18.163 \exp(-28.0 W_c)]\} 10^{-14}$, $t \geq 540s$
Diffusion coefficient in the air : $2.5 e^{-5}$
Volumetric heat capacity of fiber : $373.3 + 4661.0 W_c + 4.221 T$
Thermal conductivity of fiber :
$(38.49 - 0.720 W_c + 0.113 W_c^2 - 0.002 W_c^3) 10^{-3}$
Heat of sorption: $1602.5 \exp(-11.72 W_c) + 2522.0$
Porosity of fiber : 0.92
Density of fiber ; 1300 kg/m ³
Radius of fiber ; 1.03 e-5 m
Mass transfer coefficient : 0.137 m/s
Heat transfer coefficient : 99.4 W/m ² K

(*) The estimated values are based on data from various authors.

measured using a hot wire anemometer and humidity probe, respectively.

The electromagnetic energy was injected into the cavity of the oven. Energy uniformity was improved by rotating the load on a turntable fitted inside the microwave cavity. The presence of the turntable was also necessary to achieve the optimum performance of the oven and was designed to absorb some power to reduce the levels of reflected microwaves onto the magnetron.

EXPERIMENTAL DETAILS

The microwave source is a magnetron type AVM 610/PH/VH, with a frequency of 2.45 Ghz. Drying experiments have been performed in the laboratory test apparatus for microwave drying. The apparatus consists of a domestic microwave oven ($V = 20$ l, connected power of 1200 W, microwave output power of 580 W). Because the microwave power is too strong in comparison with the size of the sample, glass containers filled with water are put into the chamber of the microwave oven. In that way the power of microwave heating directed to the drying sample was decreased.

Ordinarily, the available microwave power in the sample cavity is determined by measuring the temperature rise of a quantity of water large enough to absorb all of the microwave energy delivered. The air flow was generated by a fan. This flow was confined in a rectangular

region to improve its intensity and minimize turbulence over the samples. For this purpose, a PTFE sheet was placed inside the oven. Metallic and mobile walls were placed inside the rectangular applicator. These mobile walls facilitate the appearance of different and time-changing electric field configurations allowing an average constant field distribution near samples. To avoid external radiation from the oven, two metallic grids were positioned at the extremes of the microwave cavity as the air was flowing. The air temperature was varied by means of electrical resistances. To measure temperatures, an optical fiber thermometer (Luxtron 790) was employed. The use of optical fibers, instead of thermocouples, was preferred so as not to perturb the electric field within the oven and in order to minimize the interferences of the electric field on the measurements. Symmetrical conditions were obtained due to the use of a grill made with PTFE strings which allowed air contact on both sides of samples. A high precision scale (Ohaus 110) measured the weight losses during drying. Likewise, the air temperature and its relative humidity were monitored by means of two sensors (Rotronic HVAC, series FTCA15) placed at the air flow inlet and outlet. To measure the absorption of liquid water in fabrics, circular samples were uniformly wetted in water and left overnight sandwiched between two wet sponges. The next day, the mass of water freely absorbed by each sample was recorded. We obtained the desired regains by drying wetted samples; approximately 10 minutes was allowed after drying for the specimen to reach uniform moisture distribution. Regain was determined shortly before the test by weighting the sample. Sample thickness was measured after conditioning to standard textile test conditions (65% RH, temperature 20°C), and the distance between the heat source and the sink was adjusted to this figure. While it was noticed that the thickness of a sample changes slightly with regain, we chose this approach for simplicity. After each test, we determined the amount of water condensed on the heat sink by blotting it with a paper tissue, which we then weighed.

RESULTS AND DISCUSSION

Figs. 1 and 2 represent the comparison between the model prediction and experiment results for the average moisture content for two different heating temperatures.

The results show a close agreement between the experimental and theoretical values. In figure 1, when heating temperature of 55°C is applied, for the first 49 minutes, slight differences is evident in the shape of the theoretical and experimental curves. However, immediately there after, a reasonable agreement is shown between the two. This can be attributed to the fact that as the moisture migrates and sample dries, the computational domain of material decreases due to the shrinkage. Consequently, the moisture content diffusion to the drying surface has a shorter distance than at the beginning of drying. This explains why for the last 50 minutes of drying all predicted values are in close agreement with the experimental data.

Figs. 3 shows that there is an increase in drying rate because of the microwave power density. This can be attributed to the effect of microwave on moisture by rapidly increasing the moisture migration to the surface and increased evaporation. A comparison of these drying curves demonstrates improvement in drying times, under microwave heating. Nevertheless the results show significant improvement in average drying times over the conventional heating method.

It can be observed from Fig. 2 that the drying rate curves are characterized by three distinct drying periods: an initial heating up period representing a transition period corresponding to non-isothermal conditions, and two falling rate periods which exhibit an exponential variation in the residual moisture with time. Hence, each of the falling rate periods can be characterized by an exponential equation

$$X = a \exp(-k_c t) \quad (4)$$

where a is the pre-exponential factor (kgkg^{-1}) which represents the initial moisture content and k_c is the exponential variable, which gives an indication of the specific drying constant (min^{-1}).

The drying rate constant, k_c , can be calculated from equation (4) for each falling rate period at different drying conditions.

The amount of energy absorbed by the water in the sample is governed by the strength of the electric field, dielectric properties and sample temperature. At higher levels of absorbed power one would expect higher sample temperature, high drying constant and faster drying. All these trends are evident in the figures.

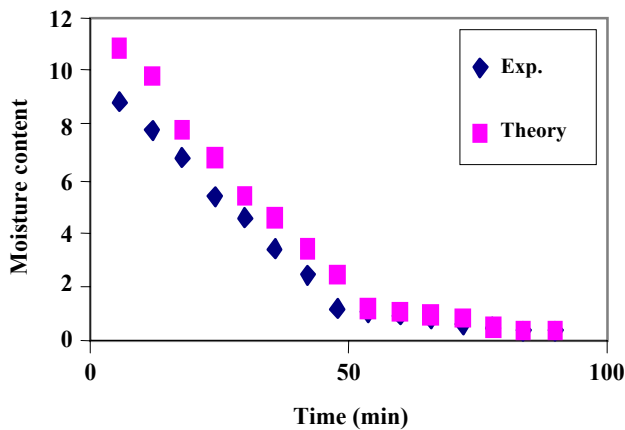


Fig. 1: Comparison of Experimental and theoretical average moisture content (kg/kg db). Microwave Heating Temp. = 55°C

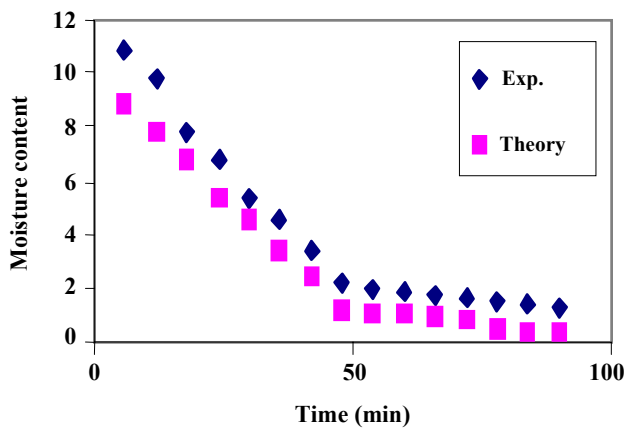


Fig. 2: Comparison of Experimental and theoretical average moisture content (kg/kg db). Microwave Heating Temp. = 40°C

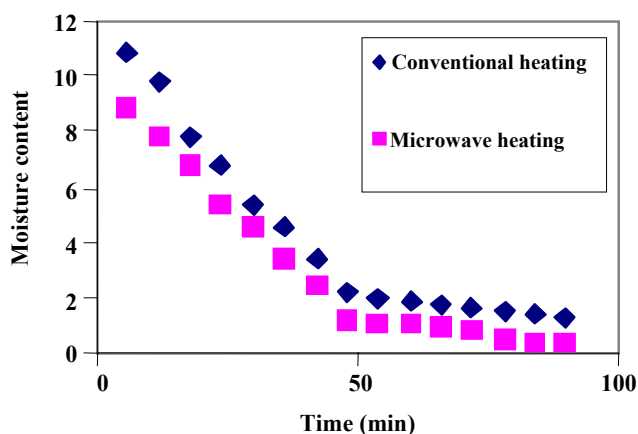


Fig. 3: Comparison of conventional and microwave heating on average moisture content (kg/kg db). Heating Temp. = 40°C.

Fig. 4 shows the effect of microwave power applied on the drying curve.

Fig. 4 also indicates that an increase in the microwave power applied produced a steeper drying curve resulting in faster removal of the moisture.

The effect of air temperature on the drying rate constant is shown in Fig. 5.

Air temperature and velocity were found to have little effect on drying rate where a slight increase in the drying constant resulted by increasing air velocity and temperature. This is attributed to the fact that microwave power is more dominant and the process does not rely on conduction since the heat is generated deep within the sample. The effect of temperature however, was more pronounced at lower levels of microwave power. Although the effect of air is limited in the presence of microwave power, its use is important in enhancing product quality and also reduction in the drying time was obtained. The presence of air at a certain velocity is also important to act as a moisture sink to carry away the moisture driven from the interior of the solid to the surface by internal heat generation caused by a microwave absorption and create a positive partial pressure gradient. An increase in sample width results in a large increase in the drying constant (Fig. 6).

Comparison between the experimental and predicted drying curves are shown in Fig. 7.

The amount of porosity, *i.e.*, the volume fraction of voids within the carpet, determines the capacity of a carpet to hold water; the greater the porosity, the more water the carpet can hold. Porosity is obtained by dividing the total volume of water extruded from the carpet sample by the volume of the sample. The most water is stored between yarns rather than within them (Fig. 8).

Liquid extrusion is a standard technique used to characterize pore size distribution in thick and thin fibrous materials [13].

The technique is simple and quick, requiring no expensive equipment and only needs a small amount of computation to complete the analysis [13]. The capacity of yarn to hold water may be estimated using the method explained in reference [14].

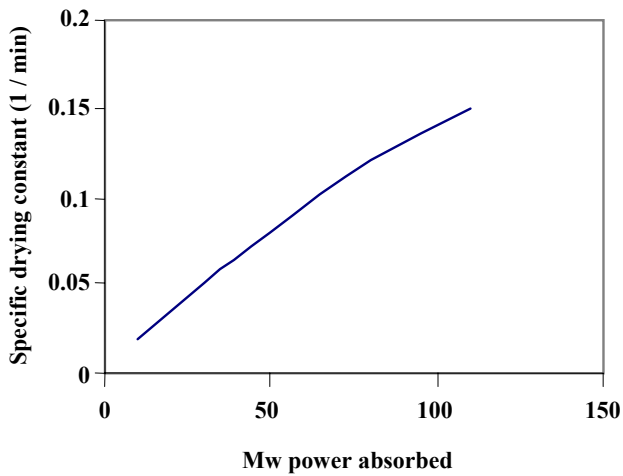


Fig. 4: Effect of microwave power absorbed on the drying constant.

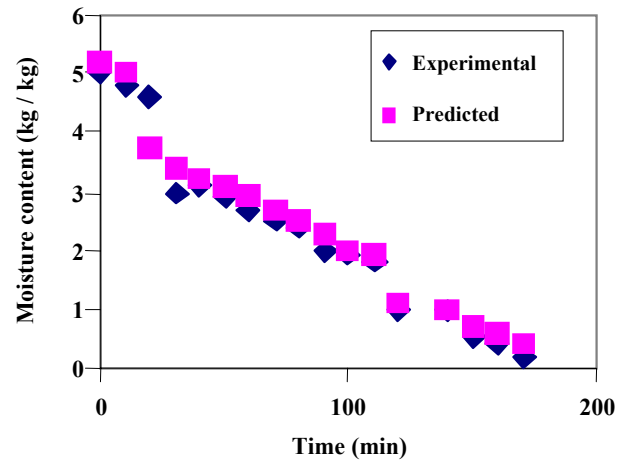


Fig. 7: Comparison between experimental and predicted drying rate.

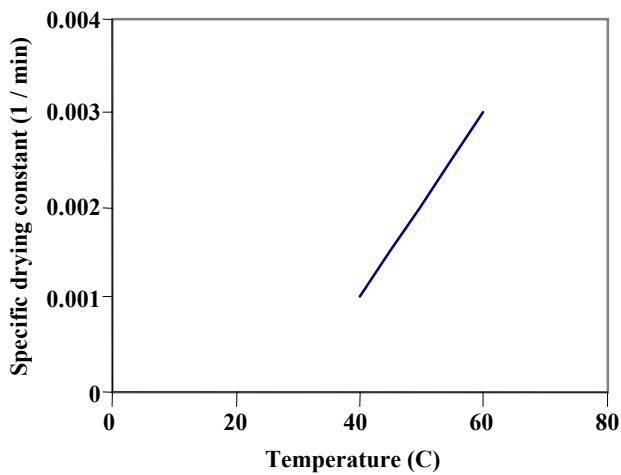


Fig. 5: Effect of air temperature on the drying rate constant.

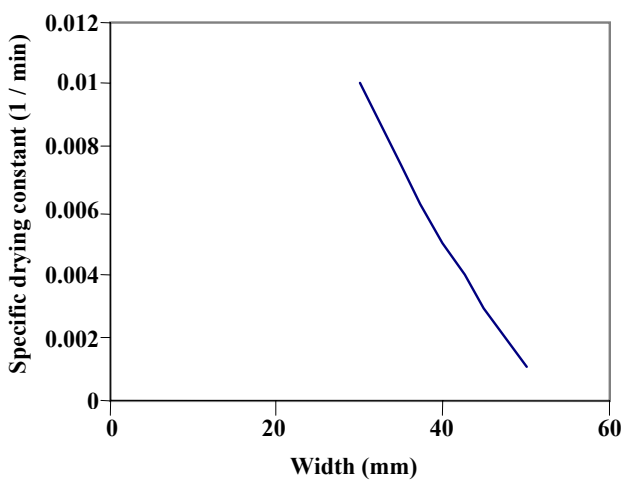
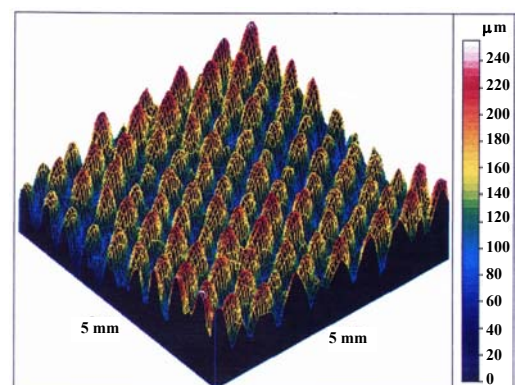
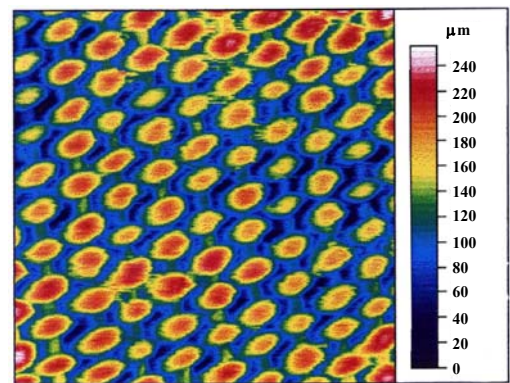


Fig. 6: Effect of sample width on the drying constant.

Fig. 8: A typical Pore size distribution.

Appendix A- Statistical Analysis

Empirical model was developed by fitting the drying constant, k_c (min^{-1}), to the design and operational condition under investigation. An empirical correlation, describing each falling rate period, was obtained which takes into account the parameters: air temperature, air velocity and microwave power. The drying process was assumed to be a system which discussed in detail in our recent published work [12]. As it is shown previously, the dependent variable or response, Y (in this study, drying constant) characterized each falling rate period. Furthermore, a mathematical function, f, was assumed to describe the relationship between response Y and the independent variables such as;

$$Y = f(T, V, MW_{ab}, W) \quad (1A)$$

Where MW_{ab} represent microwave power, T the air temperature, V the air velocity and W the sample width.

As the nature of the function, F, is unknown and in most cases it is very complex, a second degree polynomial equation was assumed to approximate the function:

$$Y = c_0 + \sum_{i=1}^3 c_i x_i + \sum_{i=1}^3 c_{ii} x_i^2 + \sum_{i=1}^2 \sum_{j=i+1}^3 c_{ij} x_i x_j \quad (2A)$$

where, c_0 , c_i and c_j are the estimated coefficients and x_i 's and x_j 's are normalized values of the independent variables under consideration.

The relationships between the drying constant and different operational parameters were represented in detail in [12] and the drying constant was found to vary linearly with each independent variable supported by high correlation coefficients. Hence the second-order polynomial equation (Eq. (3A)) can be reduced and a linear function is considered such as:

$$Y = c_0 + c_1 x_1 + c_2 x_2 + c_3 x_3 + c_4 x_4 \quad (3A)$$

The variables under investigation were normalized so that changes will have a similar order of magnitude. The correlation coefficients c_0 , c_1 , c_2 , c_3 and c_4 were calculated using a multiple linear regression analysis based on the Gauss-Jordan elimination technique. The analyses were performed using MINTAB for Windows. The correlation constants by multiple linear regression technique are shown in Table 2 with analysis of variance (ANOVA) results.

Table 2: Statistical results for modeling the drying behavior.

	Coefficient (c_i)	Estimated coefficient	Standard deviation
First period	c_0	0.01634	0.00657
	c_1	0.1089	0.00777
	c_2	0.00420	0.00814
	c_3	0.00615	0.00899
	c_4	-0.01989	0.00654
Second period	c_0	0.02450	0.0109
	c_1	0.13410	0.01387
	c_2	0.0986	0.01456
	c_3	0.01261	0.01698
	c_4	-0.03569	0.01299

The final correlation showing the relationship between the drying rate and the various operational parameters are:

-First period:

$$k_{c1} = 0.01634 + 0.1089 \left(\frac{MW_{ab}}{116} \right) + 0.0042 \left(\frac{T}{60} \right) + 0.00615 \left(\frac{V}{2} \right) - 0.01989 \left(\frac{W}{35} \right) \quad (4A)$$

-Second period:

$$k_{c2} = 0.0245 + 0.1341 \left(\frac{MW_{ab}}{116} \right) + 0.0986 \left(\frac{T}{60} \right) + 0.01261 \left(\frac{V}{2} \right) - 0.03569 \left(\frac{W}{35} \right) \quad (5A)$$

The derived formulae were used to recalculate the drying rate constant. The statistical results are shown in Table 3.

From the correlation coefficients R^2 , the predictive model is statistically acceptable at the 1% level of significance.

Appendix B- The Effective Variables

The drying rate curves were then computed using the Lagrangian differentiation technique based on five consecutive data points presented in details in our previous works[11,12]. For equally spaced time intervals, the five point equations are:

$$\frac{dX_1}{dt} = \frac{[-25X_1 + 48X_2 - 36X_3 + 16X_4 - 3X_5]}{1200\Delta t} \quad (1B)$$

Table 3: Analysis of variance for predictive drying model.

Regression	Degrees of freedom	R ²	Sum of squares	Mean square
First period	4	91.4	0.0110	0.0056
Second period	4	81.1	0.0481	0.0058

$$\frac{dX_2}{dt} = \frac{[-3X_1 - 10X_2 + 18X_3 - 6X_4 - X_5]}{1200\Delta t} \quad (2B)$$

$$\frac{dX_3}{dt} = \frac{[X_1 - 8X_2 + 8X_4 - X_5]}{1200\Delta t} \quad (3B)$$

$$\frac{dX_4}{dt} = \frac{[-X_1 + 6X_2 - 18X_3 + 10X_4 + 3X_5]}{1200\Delta t} \quad (4B)$$

$$\frac{dX_5}{dt} = \frac{[3X_1 - 16X_2 + 36X_3 - 48X_4 + 25X_5]}{1200\Delta t} \quad (5B)$$

where X_{1-5} are moisture contents (kg kg^{-1}) at times $t_{1-5}(\text{m})$.

Appendix C - Microwave Heating Basic Concept

The loss tangent can be derived from material's complex permittivity. The real component of the permittivity is called the dielectric constant whilst the imaginary component is referred to as the loss factor. The ratio of the loss factor to the dielectric constant is the loss tangent. The complex dielectric constant is given by:

$$\varepsilon = \varepsilon' - j\varepsilon'' \quad (1C)$$

Where ε is the complex permittivity, ε' is the real part of dielectric constant; ε'' is the loss factor, and $\varepsilon'/\varepsilon'' = \tan \delta$ is the loss tangent.

Knowledge of a material's dielectric properties enables the prediction of its ability to absorb energy when exposed to microwave radiation. The average power absorbed by a given volume of material when heated dielectrically is given by the equation:

$$P_{av} = \omega \varepsilon_0 \varepsilon_{eff}'' E_{rms}^2 V \quad (2C)$$

Where P_{av} is the average power absorbed (W); ω is the angular frequency of the generator (rad/s); ε_0 is the permittivity of free space; ε_{eff}'' is the effective loss factor; E is the electric field strength (V/m); and V is the volume (m^3).

The effective loss factor ε_{eff}'' includes the effects of conductivity in addition to the losses due to polarization. It provides an adequate measure of total loss, since the mechanisms contributing to losses are usually difficult to isolate in most circumstances.

Another important factor in dielectric heating is the depth of penetration of the radiation because an even field distribution in a material is essential for the uniform heating. The properties that most strongly influence the penetration depth are the dielectric properties of the material. These may vary with the free space wavelength and frequency of the propagating wave. For low loss dielectrics such as plastics ($\varepsilon'' \ll 1$) the penetration depth is given approximately by :

$$D_p = \frac{\lambda_0 \sqrt{\varepsilon'}}{2\pi \varepsilon_{eff}''} \quad (3C)$$

Where D_p is the penetration depth; λ_0 is the free space wavelength; ε' is the dielectric constant; and ε_{eff}'' is the effective loss factor.

The penetration depth increases linearly with respect to the wavelength, and also increases as the loss factor decreases. Despite this, however, penetration is not influenced significantly when increasing frequencies are used because the loss factor also drops away maintaining a reasonable balance in the above equation

As the material is heated, its moisture content decreases leading to a decrease in the loss factor. It can be seen from equation (3C) that the decrease in loss factor causes in the penetration depth of radiation.

CONCLUSION

It can be concluded that microwave power and the width of the sample were the most important variables. The study also showed that the variables were independent of each other (no interaction between them) and they may be added or removed from the model without affecting the other estimated parameters.

Acknowledgment

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Notations

a	Pre-exponential factor representing the initial moisture content (kg kg^{-1})
c	Estimated coefficient
C_p	The heat capacity (J/kg K)
D	Moisture diffusivity (m^2/s)
D_i	The diffusivity at moisture $X=\infty$ and temperature $T_m=T_r$; (m^2/s)
D_0	The diffusivity at moisture $X=0$ and temperature $T_m=T_r$; (m^2/s)
E_i	The activation energy of diffusion in wet material at $X=\infty$; (kJ/mol)
E_0	The activation energy of diffusion in dry material at $X=0$; (kJ/mol)
k	The thermal conductivity (W/mK)
k_c	Specific drying constant (min^{-1})
MW_{ab}	Microwave power absorbed (W)
Q	The microwave source term (W/m^3)
T	Air temperature ($^{\circ}\text{C}$)
t	Drying time (min)
T_m	The material temperature; ($^{\circ}\text{C}$)
V	Air velocity (ms^{-1})
W	Sample width
W_c	Water content of the fiber
X	The moisture content (kg/kg dry basis)
x_1	Normalized power absorbed ratio
x_2	Normalized air temperature ratio

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