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Drying Process of Apple Slices in Low Frequency Electromagnetic Field

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Nomenclature

D_M	Molecular diffusion coefficient
D_E	Diffusion coefficient resulting from EMF
π_M	Unit equalization coefficient
J	General diffusion coefficient
ρ	Liquid density in the volume of porous material [$kg \cdot m^{-3}$]
ρ_D	Density of liquid extracted from bulk due to diffusion [$kg \cdot m^{-3}$]
ρ_P	Density of dry state in porous material [$kg \cdot m^{-3}$]
E	Electric field intensity [$V \cdot M^{-1} = kg \cdot m \cdot s^{-3} \cdot A^{-1}$]
B	Magnetic flux density [$T = kg \cdot s^{-2} \cdot A^{-1}$]
$D_*(\varepsilon, t)$	Effective diffusion coefficient
ε	Variable porosity of dried sample
M	Mass of the moisture in porous material [kg]
Q	Heat content of the bulk due to the air flow [$J = L^2 \cdot M \cdot T^{-2}$]
Q_0	Heat quantity removed from bulk with air steam [$J = L^2 \cdot M \cdot T^{-2}$]
t	Time [sec]
t_∞	Time criterion [20 hours]
f	Frequency of electromagnetic field [$Hz = sec^{-1}$]
f_∞	Frequency criterion [100 kHz]
δ	Thickness of the sample [m]
M_0	Initial mass of the porous material [kg]
L	Initial length of the dried material [m]
L_0	Length of the material after drying [m]
$\alpha(t)$	Time dependent total diffusion coefficient
$\alpha'(t)$	Time dependent molecular diffusion coefficient
$\alpha''(t)$	Time dependent diffusion coefficient due to the effect of electromagnetic waves

Abstract*: : In this study, the heat and mass transfer equations for porous organic materials have been derived by using "two port model" and "pi theorem", and consistency of the derived equations were analyzed by considering the processes with and without electromagnetic waves. Some theoretical and experimental investigations have been performed to determine the effect of electromagnetic fields on the drying process of porous materials and calculation of concentration profiles. Also the molecular and diffusion coefficients have been analyzed empirically by using experimental results. In the experiments, apple slices were used as porous organic material. The samples were exposed to electromagnetic waves at different frequency values. For better analysis of drying process, the experiments were conducted at different temperatures and periods. It was observed that results obtained by derived semi-empirical equations have been agreed with experimental results. It is seen that the diffusion coefficient has important role in drying process and should be determined experimentally for accurate results.

Keywords: Drying process, Electromagnetic waves, Mass transfer, Two-port model

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I. INTRODUCTION

Dried porous materials are widely used in chemistry, food and agriculture industries. For this reason, the analysis of physical and chemical transformations that occurred during the drying process has great importance both for theoretical and practical purposes. Many studies on the drying process of food materials have been done by researchers in literature [1-3]. Some knowledge concerning the variation of physical parameters in the drying process has been obtained by using mathematical inference and experimental results [4-7]. Some complicated physical processes, such as fluid movement in capillary, phase change, etc., occur in a non-uniform manner in the drying process and influence the characteristics of porous materials significantly [2,4,7].

The essential mechanism of the drying process of porous materials is the extraction of the moisture from inside of the bulk to the surface by the method of diffusion transfer (molecular, Knudsen, etc.) and then the volatilization from the surface to the air medium by convective diffusion. The mass transfer in porous materials is significantly related to the geometric properties of the pores such as size, smoothness, etc. which have important roles in the determination of effective and Knudsen diffusion coefficients. For the purpose of enhancing the drying intensity, thermal fields have been used in combination with different external fields such as electrical, magnetic and electromagnetic fields [1,3,6-12]. The effect of electrical field results in displacement currents which create thermal energy.

The electrical permittivity decreases due to the magnetic fields, while the viscosity, magnetic susceptibility and density increase. The heat transfer in the medium enhances due to the effect of the magnetic field, and the electrical currents emerge in closed cycles. Since the magnetic permeability values of the phases are different, the heterogeneous structure begins to rupture and the heat energy is released. As known, each material is composed of free electrons, ions and molecules having different electromagnetic properties. In dielectric materials, "+" and "-" charges in the sample create dipoles having chaotic movement due to the external fields. Because of the effect of the electromagnetic waves the dipoles revolve, while the ions move in the direction of the field [13-15]. These dipoles change direction and shift from their average equilibrium positions periodically in accordance with the direction, frequency and amplitude of the field. These movements are accompanied with internal frictions, and as a result of these frictions heat energy is released. There are some studies in literature on the drying process of materials in the electrical field and magnetic field [7, 10, 16]. The knowledge on the analysis of the drying process at ultra high frequency (UHF-microwaves) values, which are widely used in industrial applications, have been presented in the literature [6,9-12]. It was mentioned in former studies that the heat spreads from the inside to the outside of the material in MW ovens, while it is spreading in the reverse direction in conventional ovens, since the microwaves heat up the water inside rather than the material [17, 18]. In other words, high frequency waves cannot affect the proteins, fats and carbohydrates in the material; they affect only the electrically charged structures such as water and salt. Due to this effect, the water molecules begin to spin furiously, making more than 2 billion rotations per second. The water inside of the material gets hot instantly, boils and evaporates quickly, such that some materials in tightly closed containers may explode. Intracellular fluid boils as well, and this process results in the breaking of all of the membranes and changing the bulk structure of the material in comparison to the other cooking methods. On the other side, this very high temperature due to the fast rotation of water molecules results in the formation of various substances such as carcinogens [18]. As seen from the former studies, the drying process of fruits and vegetables at very high frequency values decreases not only the drying time but also the quality of these materials. So, the effect of external fields on the drying process of porous materials has been considered and this effect has been investigated theoretically and experimentally in many studies. An inverse problem on drying process has been analyzed by considering the deformation parameters of the dried material and magnetic field in the determination of the effective coefficient of the moisture [19]. The effect of the measured moisture and the electromagnetic wave parameters on the drying kinetics have been investigated empirically for microwave drying of a capillary porous packed bed (glass beads + water), and some comments on the electromagnetic field distribution and dispersion of the moisture and the heat in the capillary porous medium have been presented [11]. The mass and heat transfer equations in a porous medium under the effect of a microwave field have been solved by using the combination of the finite differences and the finite volumes methods [12]. In the drying process performed by using the electromagnetic fields, the migration of the moisture in porous materials is composed of two components: i) migration resulting from the diffusion; ii) migration resulting from the electromagnetic fields as expressed below:

$$J = -D_M(grad\ M) - D_E(grad\ M) * \pi_M \qquad (1)$$

Thus, the drying process in the capillary porous materials must be analyzed by considering the moisture rate. The purpose of this study is to investigate the effect of low frequency electromagnetic waves on the drying process of porous materials empirically, to model the process and to estimate the molecular and electromagnetic diffusion coefficients.

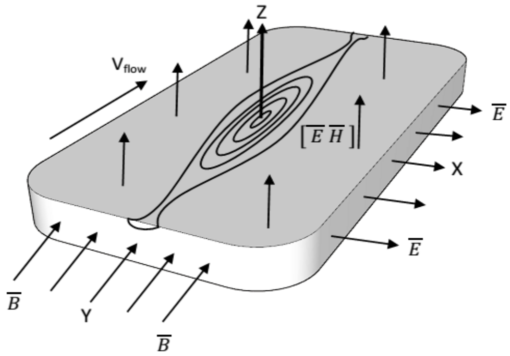

Fig. 1. The distribution of electromagnetic field vectors on the apple slice.

II. ELECTROMAGNETIC WAVES AND MASS TRANSFER IN DRYING PROCESS

The heat-mass transfer results from the change of the micro-structural and physical parameters of the mass of the porous materials due to the drying process. The intrinsic parameters of the porous materials are the density, the porosity, the effective diffusivity and the electromagnetic diffusivity which are related to each other. The relationship between the density and porosity can be expressed as $\varepsilon = 1 - \rho/\rho_p$.

It has been observed from the former studies performed that when determining the effects of the moisture and heat, the density and the diffusivity of the material had decreased from a definite maximum value nonlinearly due to the drying process [12, 16, 20, 21]. For this reason, the drying process of the deformed porous materials is generally characterized by the variable values of the density, the porosity and the effective diffusivity.

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Apple slices of 10x50x60 mm^3 were used to analyze the effect of electromagnetic fields on the drying process of porous materials as shown in Fig. 1. The apple slice has experienced the electromagnetic waves resulting from magnetic flux density of *B* and the electrical field intensity of *E* in a constant temperature laminar air flow medium having a velocity of *v* [4,14, 15]. The mass transfer expression for an apple slice is written as:

$$\frac{\partial M}{\partial t}+V_x\frac{\partial M}{\partial x}+V_y\frac{\partial M}{\partial y}=\frac{\partial}{\partial y}\left[D_*(\varepsilon,t,y)\frac{\partial M}{\partial y}\right]+\dots$$
$$\dots+\frac{\partial}{\partial x}\left[D_*(\varepsilon,t,y)\frac{\partial M}{\partial x}\right]+\frac{\partial}{\partial y}\left[\pi_M D_E(y)\frac{\partial M}{\partial y}\right]\dots$$
$$\dots\ \frac{\partial}{\partial x}\left[\pi_M D_E(x)\frac{\partial M}{\partial x}\right] \quad (2)$$

In (2), the first and second terms are convective diffusion, and the third and fourth terms characterize the mass transfer due to the electromagnetic diffusion. If the convective part of the general mass transfer given in (2) is shown by M' *and* the part resulting from the electromagnetic field is shown by M'' then M can be written as

$$M=M'+M'' \quad (3)$$

It must be noted that the main moisture migration occurs in the direction of y axis, so if the low mass transfer occurring in the direction of x axis is ignored, then (2) can be written in form of two independent equations by considering (3) as expressed below:

$$\frac{\partial M'}{\partial t}+V_y\frac{\partial M'}{\partial y}=\frac{\partial}{\partial y}\left[D_*(y)\frac{\partial M'}{\partial y}\right] \quad (4a)$$

$$\frac{\partial M''}{\partial t}+V_y\frac{\partial M''}{\partial y}=\frac{\partial}{\partial y}\left[\pi_M D_E\frac{\partial M''}{\partial y}\right] \quad (4b)$$

As seen, (4) is nonlinear and difficult to solve. So, it is required to use phenomenological methods to solve this equation by considering that the mass flow has a variable character. (4a) can be solved as follows:

In order to model the heat and mass transfer by convection, Two Port Method and π Theorem, which are important and often-used modelling methods in electronics and electrotechnics, were utilized as seen in Fig.2. In this method, any circuit component or part, which has four terminals, is denoted as a box, and convenient input and output parameters are determined for the given system. The purpose of this method is to establish a relationship between input and output parameters. The following equations can be written by using two port theorem according to the model given in Fig. 2.

$$\rho=A_{11}\rho_0+A_{12}Q_0 \qquad Q=A_{21}\rho_0+A_{22}Q_0 \quad (5)$$

where A_{ij} are the coefficients which characterize the physical and chemical properties of the porous material, and these coefficients are determined by considering the initial conditions.

$$A_{11}=\left.\frac{\rho}{\rho_0}\right|_{Q=0};\ A_{12}=\left.\frac{\rho}{Q_0}\right|_{\rho_0=0};$$
$$A_{21}=\left.\frac{Q}{\rho_0}\right|_{Q=0};\ A_{22}=\left.\frac{Q}{Q_0}\right|_{\rho_0=0} \quad (6)$$

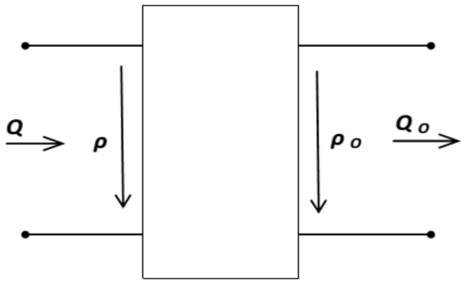

Fig. 2. Scheme of two port method

Then, considering the initial conditions in (5) and using the methods given in former studies [12, 16, 20], one can obtain (7) as follows:

$$\frac{M'}{M_0}\left[1{,}04+13{,}725\ \frac{[L^2.t^{-1}][T][t^2]}{[L_0^2.t^{-1}][T_\infty][t_\infty^2]}\right]=1 \quad (7)$$

Using π theorem, (7) can be written as

$$\frac{M'}{M_0}=[1{,}04+13{,}725\cdot\propto'(t)\frac{T}{T_\infty}.(\frac{t}{t_\infty})^2]^{-1} \quad (8)$$

where $\propto'(t)$is the empirically obtained molecular diffusion coefficient.

III. ELECTROMAGNETIC WAVES AND DRYING PROCESS OF POROUS MATERIALS

T As seen in Fig. 1, $\bar{E}$ has a component only in x axis, also $\bar{H}$ has a component only in y axis [14,15]. The distribution of the electromagnetic waves along the z axis, which are composed of these two components, was shown in Fig. 3. $\bar{E}$ vector can be written as

$$\bar{E}=E_0\,e^{-\gamma z}\,\bar{a}_x \quad (9)$$

The relationship between $\bar{E}$ and $\bar{H}$ vectors can be expressed as

$$\bar{H}=\sqrt{\frac{\sigma+jw\varepsilon}{jw\mu}}\cdot E_0e^{-\gamma z}\,\bar{a}_y \quad (10)$$

So, the characteristic impedance of the waves moving along the z axis is given as

$$\eta=\frac{E_x}{H_y} \quad (11)$$

By considering the (9), (10) and (11), the following equations are obtained as

$$\eta=\sqrt{\frac{j\,w\,\mu}{\sigma+j\,w\,\varepsilon}}=\sqrt{\frac{\mu/_\varepsilon}{\sqrt{1+\frac{\sigma}{w\,\varepsilon}}}}\,e^{j\,\theta} \quad (12)$$

$$tg\,2\theta=\frac{\sigma}{w\,\varepsilon} \quad (13)$$

where μ and ε are the magnetic susceptibility and electrical permittivity of the medium, respectively. $\mu_r\approx1$ and $\varepsilon_r\geq100$, since a fresh apple contains a definite amount of water which is a diamagnetic material. For this reason, μ is equal to $\mu_0=4\pi\cdot10^{-7}\ N/A^2$, and ε is equal to $\varepsilon_r\,\varepsilon_0\approx150\,\varepsilon_0\approx1.33*10^{-9}\ C^2/N\cdot M^2$.

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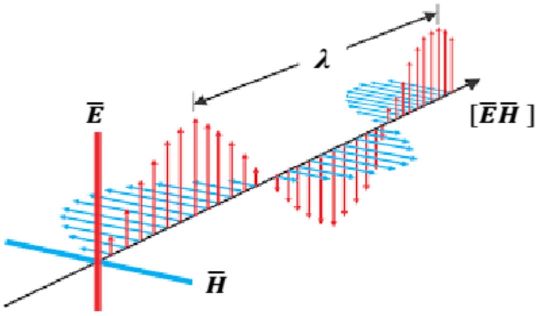

Fig. 3. The distribution of electromagnetic wave along z axis, [ĒH̄].

The electrical permittivity of the sample was determined for definite frequency values at different temperatures experimentally. Then, the following expression was obtained by using the analyses given in literature [16, 20] to calculate the amount of moisture removed from the sample by the effect of the electromagnetic waves:

$$\frac{M''}{M_0} = 120\,[(\frac{f}{f_\infty})^2\,(\frac{t}{t_\infty})^3 \propto''(t)]^{-1} \qquad (14)$$

where $\propto''$ (t) is the diffusion coefficient resulting from the effect of electromagnetic waves.

IV. EXPERIMENTAL INVESTIGATION OF ELECTROMAGNETIC DRYING PROCESS

If you are It was observed from the experiments conducted to determine the effect of electromagnetic materials on the drying process of porous materials that the intensity of the drying process increased while the drying period decreased. As mentioned above, there are a few numbers of studies about the drying of fruits and vegetables in magnetic, electric and electromagnetic fields. Generally, the high frequency microwaves were used in the drying processes, and some experimental and theoretical results were submitted in the former studies. Although the microwave drying causes lower the drying periods, the studies about the drawbacks of the microwave drying is limited. Currently, researchers are conducting a lot of studies concerning the determination of the effect of the microwaves on the human organism and the dried material. In these studies the researchers have also investigated the negative effects such as the changes in the microstructure of the porous materials, the decrease in the material quality [22-25].

In this study, the results of the experimental and theoretical investigations to determine the effect of low frequency (0-10 kHz) electromagnetic waves on the intensity of the drying process of fruits and vegetables have been presented. In order to analyze the drying process, the apple slices shown in Fig. 1 were used. A special drying machine was designed and installed for the experiments [19].

The experiments were conducted under the conditions of different frequencies, *f*=0-10 kHz, different temperatures, *T*=40-60°C, and different air flow velocities, *v*=1.0-2.0 m/s. The sample was placed on the perforated plastic material mounted on the drying chamber where the temperature and air flow are constant. The mass, moisture and temperature were measured in the periods of Δ*t*=1 hour by using a computer controlled system. The system has the capability of changing the frequency of electromagnetic waves, the velocity of air flow and the temperature. In the light of the conducted experiments, the diffusion coefficients were determined in the case of a drying process under the effect of electromagnetic waves. In theoretical analysis, (15), which was obtained by inserting (8) and (14) into (3), was used to determine the moisture concentration for different variable parameters.

$$\frac{M}{M_0} = \frac{1}{1{,}04+[13{,}725\,\frac{T}{T\infty}\cdot(\frac{t}{t\infty})^2+120\,(\frac{f}{f\infty})^2(\frac{t}{t\infty})^3]\alpha(t)} \qquad (15)$$

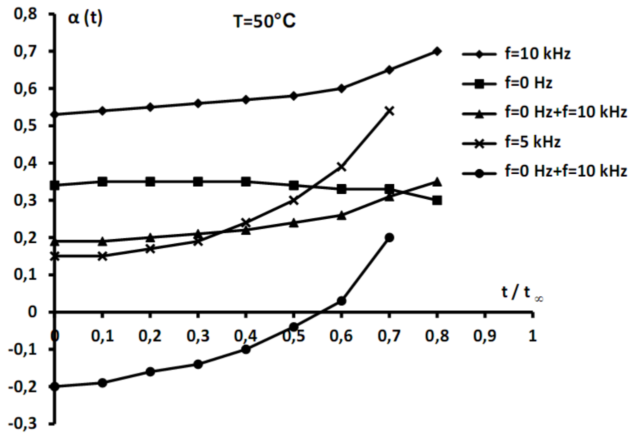

Fig. 4. Diffusion coefficients vs. t / t∞ curves obtained by empirical equation for different freq. values at 323°K (t_∞ =20 h).

Table-I:. Experimental results for α (t) at 323°K, t∞ =20 h

α (t)	Frequency				
t / t ∞	**0 kHz**	**5 kHz**	**10 kHz**	**0 Hz + 5 kHz**	**0 Hz + 10 kHz**
0,1	0,3467	0,1615	0,5365	-0,1852	0,1898
0,2	0,3457	0,1742	0,5423	-0,1715	0,1966
0,3	0,3440	0,1976	0,5520	-0,1464	0,2100
0,4	0,3417	0,2358	0,5660	-0,1059	0,2243
0,5	0,3387	0,2960	0,5845	0,0427	0,2458
0,6	0,3353	0,3909	0,6078	0,0556	0,2725
0,7	0,3312	0,5428	0,6367	0,2116	0,3055
0,8	0,3269	0,7533	0,6717	0,2270	0,3452

As seen (15), which is very important to define the drying characteristics of the sample, strongly depends on the diffusion coefficient *α (t)* besides the other parameters such as *T* and *f*. The variation of diffusion coefficient versus normalized time was presented for different frequency values at 50°C in Table I and Fig. 4.

In the drying process of apple slices, the moisture concentration for experimental results and theoretical results obtained by (15) were presented for the conditions of different temperatures, different frequency values and constant air flow velocity of *v*=2 m/sec in Tables II, III and IV and Figs. 5, 6, 7. For better analysis, the curves of the results obtained for *f*=0 were presented in figures. As seen from the curves, the effect of electromagnetic waves on drying process significantly depends on the frequency of the electromagnetic field and diffusion coefficient.

Table-II: Experimental results for M / M $_0$ vs. time at 313°K

M / M $_0$	Frequency		
Time	0 kHz	5 kHz	10 kHz
0 hour	1	1	1
4 hours	0,81	0,91	0,71
8 hours	0,66	0,79	0,48
12 hours	0,47	0,51	0,32
16 hours	0,32	0,31	0,31
20 hours	0,26	0,16	0,21
24 hours	0,19	0,14	0,15

$$\alpha(t) = 1.1^{-\left(\frac{t}{t\infty}\right)^2} \cdot 0.27 \quad ;\ f= 0$$

$$\alpha(t) = 0.25^{-\left(\frac{t}{t\infty}\right)^2} \cdot 0.11025 \quad ;\ f= 5\ kHz$$

$$\alpha(t) = 2.05^{-\left(\frac{t}{t\infty}\right)^2} \cdot 0.5325 \quad ;\ f= 10\ kHz$$

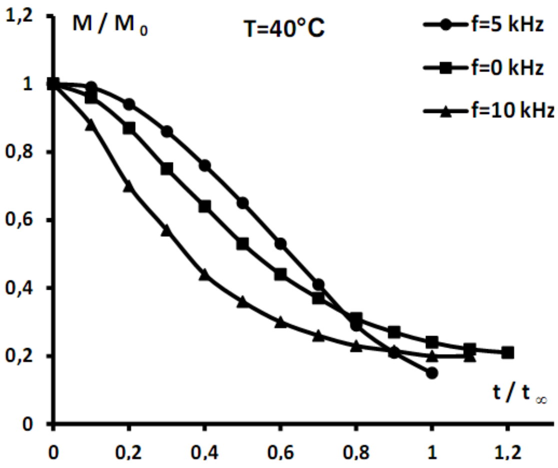

Fig. 5. Normalized *M* vs. *t* curves obtained by empirical (15) at 313°K

V. RESULTS AND DISCUDDION

In this study, the results of the theoretical and experimental analysis of drying process of porous materials with and without electromagnetic waves in definite conditions were presented. The experiments were conducted for different temperature values of *T*=313 K, 323 K, 333 K (40°C, 50°C, 60°C), different frequency values of *f*=5, 10, 15 kHz. The velocity of air flow was taken as a constant of *v*=2 m/sec.

Table-III: Experimental results for M / M $_0$ vs. time at 323°K

M / M $_0$	Frequency		
Time	0 kHz	5 kHz	10 kHz
0 hour	1	1	1
2 hours	0,91	0,97	0,83
4 hours	0,81	0,92	0,58
6 hours	0,74	0,56	0,55
8 hours	0,71	0,41	0,41
12 hours	0,52	0,29	0,21
16 hours	0,27	0,19	0,17
20 hours	0,21	0,16	0,16

$$\alpha(t) = 1.1^{-\left(\frac{t}{t\infty}\right)^2} \cdot 0.347 \quad ;\ f= 0$$

$$\alpha(t) = 0.08^{-\left(\frac{t}{t\infty}\right)^2} \cdot 0.1574 \quad ;\ f= 5\ kHz$$

$$\alpha(t) = 0.7^{-\left(\frac{t}{t\infty}\right)^2} \cdot 0.5346 \quad ;\ f= 10\ kHz$$

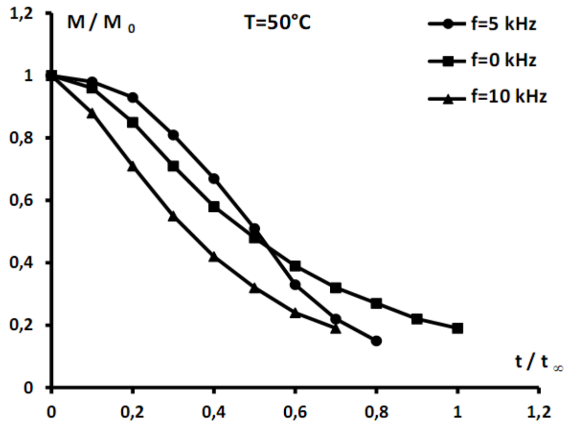

Fig. 6. Normalized *M* vs. *t* curves obtained by empirical (15) at 323°K

The mathematical model of the drying process and the effect of the electromagnetic waves were given in (4a) and (4b), respectively. In order to find the approximate solution of the multivariable nonlinear (4a), a two port model of the drying process was established and analyzed by using Pi-theorem, and then (8) was obtained. In this equation, $\alpha'(t)$ denotes molecular diffusion coefficient and is a nonlinear term. The approximate solution of the nonlinear (4b) was analyzed with the methods of electromagnetic field theory, and (14) was obtained by using Pi-theorem. In this equation, the nonlinear coefficient of $\alpha''(t)$ is the diffusivity resulting from electromagnetic waves. It must be noted that it is possible to determine the molecular diffusion coefficient by using empirical methods. But it is not possible to determine the electromagnetic diffusivity empirically, since the electromagnetic waves increase the effect of the convective method and do not cause any additional mass transfer. In order to determine the electromagnetic diffusivity, at first the general diffusion coefficient of α (t) in (15) must be determined. Then, the electromagnetic diffusivity can be determined by simple calculations. The obtained experimental and theoretical results for the values of diffusion coefficients at 323°K were given in Fig. 4. As seen from the figure, the electromagnetic diffusion coefficient was very low for the first 11 hours of the drying process at 5 kHz, in other words it affected the drying process slightly. Then, it increased swiftly and accelerated the mass transfer after the first 11 hours, so the drying process ended earlier (Fig. 6).

Table-IV: Experimental results for M / M $_0$ vs. time at 333°K

M / M $_0$	Frequency		
Time	0 kHz	5 kHz	10 kHz
0 hour	1	1	1
2 hours	0,86	0,96	0,74

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4 hours	0,64	0,86	0,43
6 hours	0,42	0,58	0,31
8 hours	0,31	0,37	0,24
10 hours	0,26	0,22	0,21
14 hours	0,19	0,15	0,13

$$\alpha(t) = 1.1^{-\left(\frac{t}{t_\infty}\right)^2} \cdot 1.122 \qquad ; f=0$$

$$\alpha(t) = 0.02^{-\left(\frac{t}{t_\infty}\right)^2} \cdot 0.4267 \qquad ; f=5\text{ kHz}$$

$$\alpha(t) = 1.7^{-\left(\frac{t}{t_\infty}\right)^2} \cdot 1.382 \qquad ; f=10\text{ kHz}$$

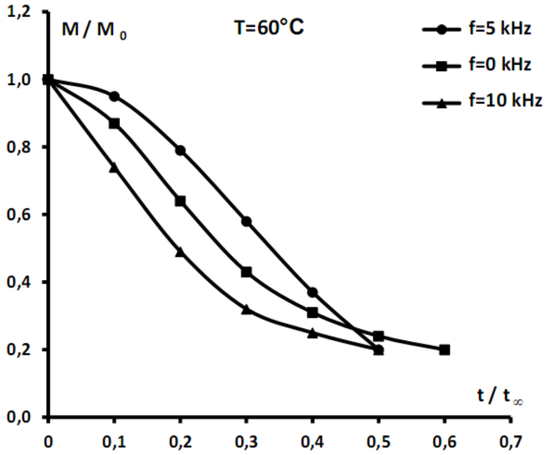

Fig. 7. Normalized *M* vs. *t* curves obtained by empirical (15) at 333°K

The similar situation was observed for other temperature values as seen in Figs. 5 and 7. The frequency value of 15 kHz was tested, but it was not considered in this study, since it had negligible effects on the drying process. Also, the temperature values over 343°K were not considered, since the phase of the process changed from drying to cooking, and the internal structure and quality of the sample changed. Contrary to expectations, the drying process realized at f=0 Hz yielded better results in comparison to the process realized at f=5 kHz in short time intervals such as 4 to 10 hours. But as the period was prolonged, the process at 5 kHz dominated. The normalized mass transfer vs. time curves obtained by using (15) and corresponding experimental results were given in Figs. 5, 6, 7 and Tables II, III and IV for different temperature and frequency values, respectively. Since, (15) strongly depends on diffusion coefficient- $\alpha(t)$, the values of $\alpha(t)$ for different frequency and temperature values were given under the related tables. As seen from the figures the best drying results were obtained at 10 kHz and 60°C.

VI. CONCLUSIONS

It should be considered that both interior and exterior parts of the porous materials change their shape as a result of the drying process, and this causes a change in the pores and effective diffusion coefficient. The existing symmetry is broken down, and the form of the sample changes in an anisotropic manner, so it becomes very difficult to characterize this situation by using conventional mass transfer equations.

In this study, a mass transfer equation for a porous organic material, an apple, was derived and analyzed by considering the drying process with and without electromagnetic waves. The results obtained by using mass transfer equation, which was derived by using a two port model and pi theorem generally used in electrical engineering, were compared to the experimental results, and it was seen that the results of the derived equation were in accordance with the experimental results considerably. Also, it was observed that the diffusion coefficient was one of the most important factors influencing the drying process significantly and had to be obtained experimentally to get accurate results.

It is obviously seen from this study that the collaboration of electromagnetic waves with the conventional convective heat method has increased the intensity of the drying process and decreased the drying time as seen from Figs. 4, 5 and 6. This case also caused the heat energy to decrease. It must be noted that the usage of very high frequency electromagnetic waves (microwaves) causes a decrease in the quality of the nutrients due to the change in the microstructure of the material. For this reason, it is advised to restrict the amount of the frequency of electromagnetic waves used during the drying process of fruits containing nutrients.

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