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MODELLING A MICROWAVE/CONVECTION DRYER FOR DRYING OF POTATO SLICES

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ABSTRACT

*The aim of the present study is modeling a developed microwave/convection dryer using similitude analysis for drying a thin layer of potato slices (**Solanum Tuberosum**), which can be helpful in design and operation criterion of this developed thin layer dryer type for drying other agricultural products. Drying time as affected by microwave power and drying air temperature, effective diffusivity "D_{eff}", compatibility of experimental data to Lewis Newton's thin layer drying model and rehydration and color as quality indicators were also studied. Four different levels of microwave power, namely: 85, 175, 250 and 320W, three different drying air temperatures of drying air are 40, 50 and 60°C with air velocity of 1.5 m/s were studied. The results show that the drying time was decreased by increasing microwave power and air temperature. The effective moisture diffusivity "D_{eff}" increased with decreasing moisture content, maximum values of "D_{eff}" were recorded at highest microwave power of 320 W. Lewis Newton's thin layer drying model was highly compatible to experimental data with R^2 ranging between 0.754 to 1.00. The rehydration ratios ranged between 2.19 to 3.41 under various drying conditions. There is no significant change in color of the dried potato compared to fresh potato slices.*

1. INTRODUCTION

During conventional air drying process, heat transfer is limited by the low thermal conductivity of biomaterials, the low energy efficiency, and the beginning of the air heating, but falls rapidly with the reduction of moisture content during the falling rate period. The use of microwave can eliminate these problems by the fast and effective thermal process. Microwaves are electromagnetic waves in the frequency range of 300 MHz to 300 GHz (equivalent to wavelength of 1 – 0.1 m),

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generated by vacuum tube devices called magnetrons and klystrons that were originally developed for radar applications. Magnetrons are currently available at power levels from a few hundred watts to 50kW. All commercial and consumer microwave ovens operate at 915 and 2450 MHz. Electromagnetic energy at 915 and 2450 MHz can be absorbed by water containing materials or other ``lossy" substances, such as carbon and some organics, and converted to heat **(Khraisheh et al., 1997)**.

The drying time can be reduced by using microwave energy, which is rapidly absorbed by the product water molecules and consequently results in rapid evaporation of water and thus higher drying rates. The interior temperature of dried microwave-heated food is higher than the surface temperature and moisture is transferred to the surface more dynamically than during convective drying **(Torringa et al., 2001)**. The main advantages of microwave processing come from its ability of high-energy conversion efficiency, rapid heat transfer process, and volumetric heating. During microwave drying process, local pressure and temperature rise continuously even though the loss factor of treated materials decrease with the reduction of moisture content **(Zhou et al., 1994)**. Although these increases of pressure and temperature can speed up the drying process, they may cause side effects such as bio-value duration, physical damages, and non-uniform temperature distribution in treated materials **(Shivhare et al., 1991, Yongsawatdigul and Gunasekaran, 1996)**. Currently, microwaves have already had their positions in many industrial applications including drying, heating, tempering, sintering, vulcanization, pasteurization, sterilization, blanching, and cooking **(Sanga et al., 2000)**. They summarized advantages of microwave drying technique as:

- Instantaneous start-up and rapid heating increases production, reduces product cost and labor.
- Higher inside temperature than outside gives rise to a pressure gradient that drives the vapor to the surface.
- Selecting heating and drying due to the greater dielectric losses of water as compared to the product to be dried.
- Volumetric distributions of energy within the material improve quality and avoid surface limitations.

- Thorough drying of wet materials with low thermal conductivity.
- Economy of energy can be realized because of rapid heating and the inherent property of non-heating of the environment.
- Electromagnetic heating is non-polluting, easy to apply and be automated.

Sharma and Prasad (2001) dried garlic cloves using hot air and combined microwave- hot air drying methods in an experimental dryer. The combined microwave-hot air drying experiments were carried out with 100 g sample at temperatures of 40°C, 50 °C, 60 °C and 70 °C at air velocities of 1.0 and 2.0 m/s, using continuous microwave power of 40 W. Same sample sizes were taken for hot air drying, air temperatures and air velocity were 60°C and 70°C, and 2.0 m/s respectively. The total drying time, the color and flavor strength of dried garlic cloves were used to evaluate the performance of the combined microwave-hot air drying and the conventional hot air drying processes. Combined microwave-hot air drying resulted in a reduction in the drying time to an extent of 80 – 90% in comparison to conventional hot air drying and a superior quality of final product.

Reddy (2006) indicated that the drying time was reduced by nearly 45% with the combination mode (microwave drying + hot air drying) compared to hot air drying, for untreated and treated berries. Microwave drying also reduced the drying time considerably over hot air drying in both cases. Microwave drying had relatively higher drying rates than convection one and this was due to the higher dielectric loss factor value in osmotic dehydrated berries that favor microwave absorption. Microwave combination drying was efficient with time and energy consumption by up to 20% than microwave-only.

Several researchers manipulate similitude application for drying to increase the efficiency of research accomplishment.

2. MATERIAL AND METHODS

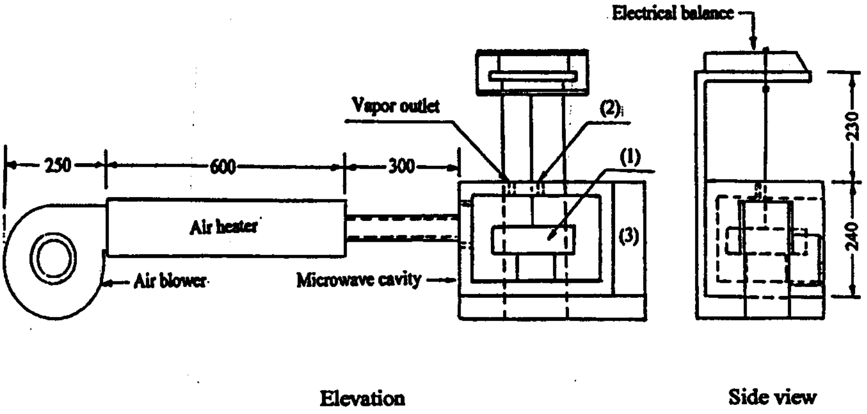
2.1. MATERIAL:

2.1.1. Raw material:

A fresh potato with initial moisture content 83 % (wet basis) was obtained from a local market. Prior drying, samples of potato were washed, peeled and sliced having a thickness of 2 mm. The sliced potato was immersed in hot water blanching by holding in boiling water (100 °C) for 3 minutes to inactivate peroxidase.

2.1.2. Microwave/convection dryer construction:

Microwave /convection dryer consisted of: domestic microwave oven, air blower, electrical heater and electrical balance as shown in fig. (1). A domestic microwave oven was used 700 W, 220 – 230 V, 2450 MHz, 5 levels of power, model N.SMB177KEB – POOC, made in Germany. The microwave oven having inside chamber dimensions of 300 width × 180 high × 260 depth mm was modified and developed to be a microwave/convection dryer. Circular opening with a diameter of 50 mm was made in one side of microwave cavity for supplying hot air to it. In the left inner side, there is a perforated steel net with dimensions of 150 mm × 70 mm for distributing air inside the microwave cavity and to prevent microwave radiation leakage. In the top of the microwave oven there are shield holes for air exhausting and to prevent microwave radiation leakage. A small air blower of 300 W, 220 V, made in China was used to supply the hot air flow rate. This blower was connected to the microwave chamber by means of housing with dimensions of 600 mm length, 100 mm width, 100 mm high made of galvanized iron sheet of 0.6 mm thickness and insulated from the outside by glass wool with thickness of 30 mm to prevent heat loss. The electrical heater of 2 kW was fixed inside the housing to heat the drying air. The housing is connected to PVC tube diameter of 50 mm, insulated also by glass wool of thickness 30 mm, this tube passes the hot air through the microwave cavity. Sample holder is made of a plastic circular housing 200 mm diameter, with 8 mm holes at the bottom. Its sides have about 90% openings of their area to permit drying air circulation. During drying, the sample holder is rested on a plastic tube of 80 mm diameter 50 mm high and directly supported to the microwave glass dish of 250 mm diameter, rotating with 10 r.p.m.



Elevation

Side view

1- Sample holder 2- Hole of sample temp. sensor 3- Control unit Dimensions in mm

Fig. (1): Elevation and side view of microwave/convection dryer.

The sample holder and specimen mass is transferred through a plastic thread penetrating the microwave ceiling and directly supported to sensitive electrical balance of 0.0001g accuracy.

2.1.3. Instrumentations:

2.1.3.1. Thermocouple:

Temperatures of the samples were measured during drying using type-K thermo couple, through a small hole at the top of the microwave oven. Thermocouples are U.S.A. manufactured, model 8528-40, and accuracy 1°C.

2.1.3.2. Thermostat:

Drying air temperature was controlled using thermostat made in Germany, accuracy 1 °C. This thermostat has been connected with the circuit of the air heater.

2.1.3.3. Electrical balance:

A digital balance (HR-200, max 210g, made in Japan) of accuracy 0.0001g.

2.1.3.4. Turbo meter:

A turbo meter was used for measuring of the drying air speed. It is manufactured in U.S.A. by Davis instruments, measuring range of (0 – 44.8) m/s.

2.2. METHODS:

2.2.1. The experiments procedure:

The microwave /convection dryer is constructed and tested at the workshop of the Agricultural Engineering Department, Faculty of Agriculture, Al-Azhar University, Nasr City, Cairo, in 2010 – 2011.

Potato was washed, peeled, sliced with a thickness 2 mm, immersed in water at (100 °C) to 3 min. and initial moisture content is measured. Drying experiments were carried out on 100 gram samples of sliced potato with three replicates. During the drying, every five minutes, the following items were recorded: drying air temperature, sample temperature, mass of sample for moisture content, diffusion and drying rates determination.

Experiments were carried out with four levels of microwave power (85, 175, 250 and 320 W) and three drying air temperatures of (40, 50 and 60 °C) and air velocity 1.5 m/s.

Quality tests, as slice rehydration and color, have been carried out to each of fresh and dried products.

2.2.2. Determination of magnetron output power:

The output power of the magnetron was measured by the calorimetric method (**Mataxas and Meredith, 1983; Tulasidas et al., 1993**). 1000 g of distilled water was taken in a glass beaker and its temperature was measured by mercury thermometer. The beaker was kept in the center of microwave oven and was exposed to microwaves for a predetermined period of time (62 s). The water was taken out immediately and stirred quickly by a glass rod and its temperature was again measured by the thermometer. The output power of magnetron was estimated by estimating the power absorbed by water.

2.2.3. The initial moisture content of samples:

The initial moisture content of samples was determined in an oven at temperature of 105 °C for 24 hours (ASAE standards, 1991).

2.2.4. Moisture content of sample during drying:

- Moisture content (m_t), (wet basis %):

The moisture content, wet basis % is determined as follows:

$$m_t = \frac{B - A(1 - m_i)}{B} \rightarrow (1)$$

Where A is the mass of fresh sample (g), B mass of sample at any time (g) and m_i initial moisture content, w.b. %.

- Moisture content (M_t), (dry basis %):

The moisture content, dry basis % is determined as follows:

$$M_t = \frac{B}{A}(1+M_i)-1 \qquad \rightarrow (2)$$

Where Mi: initial moisture content, d.b. %.

2.2.5. Analytical study:

Dimensional analysis technique was used to develop a prediction model for thin layer drying of potato slices by microwave/convection dryer. Based on the Buckingham Pi theorem **(langhaar, 1951)**.

Six variables are presented in table (1). Basic dimensions are mass (M), length (L) and time (t). The moisture ratio required can be expressed as a function of other five variables, $MR = f(P, P_u, v, \phi, \lambda)$

Table (1): Study variables:

NO	Symbol	Description	Dimension	Units
1	MR	Moisture ratio	Dimensionless	--
2	P	Input heating rate	$M\,L^2t^{-3}$	kJ/s
3	P_u	Useful drying energy rate	$M\,L^2t^{-3}$	kJ/s
4	v	Air velocity	Lt^{-1}	m/s
5	ϕ	Elapsed time of drying	t	s
6	λ	Characteristic length	L	m

The following dimensionless groups obtained:

$$P_{i1} = MR, \quad P_{i2} = \frac{v \cdot \phi}{\lambda} \quad \text{and} \quad P_{i3} = \frac{P_u}{P}$$

The following functional form is suggested:

$$MR = f\left(\frac{v \cdot \phi}{\lambda}, \frac{P_u}{P}\right) \qquad \rightarrow (3)$$

The circulation parameter ($P_{i2} = v.\phi/\lambda$) agreed with that predicted by **(Ghanem, 1998)** in his work of solar manure drying. **(Ghanem, 2010)** also predicted a similar group in his work of refractance window dryer for liquid foods. The parameter ($P_{i3} = Pu/P$) termed as energy efficiency also previously predicted by **(Ghanem, 2010)**.

The following measurements were carried out for determining proportional constants of the dimensional analysis:-

- Moisture ratio calculation (*MR*):

$$MR = \frac{M_t - M_e}{M_i - M_e} \qquad \rightarrow (4)$$

Where M_e is the equilibrium moisture content, can be assumed $M_e = M_f$ (M_f is final moisture content).

- Input heating rate (*P*):

$$P = P_m + P_a \qquad \rightarrow (5)$$

Where P_m is the microwave heating rate (kJ/s) and P_a air heating rate.

$$P_a = v \cdot a \cdot \rho \cdot c_p \cdot \Delta T \qquad \rightarrow (6)$$

Where v is the air velocity (m/s),a sectional area of air inlet (m^2), ρ air density (kg/m^3) at drying temperature, C_p specific heat of air (kJ/kg.°K) at drying temperature and ΔT temperature difference between inlet and outlet of air (°K).

- Useful drying energy rate (P_u):

$$P_u = (m \cdot c_p \cdot \Delta T + w_w \cdot l) / \phi \qquad \rightarrow (7)$$

Where m is mass of the sample to be dried (kg), ΔT temperature difference of sample (°K), w_w amount of water removed (kg), L latent heat of vaporization at sample temperature (kJ/kg) and c_p specific heat of the sample (kJ/kg.°K), evaluated as a function of moisture content according to **(Toledo, 1991):**

$$cp = 4.1868 m_{w.b.} + 0.83736 \cdot (1 - m_{wb}) \qquad \rightarrow (8)$$

The removed water (w_w) was calculated by the following equation:

$$w_w = \frac{A(m_i - m_f)}{(100 - m_f)} \qquad \rightarrow (9)$$

Where m_i is the initial moisture content, w.b. %, m_f final moisture content, w.b. % and A initial mass of material (kg),

- Characteristic length (λ)

The characteristic length of the drying bin is determined as follows:

$$\lambda = 4 \cdot A_s / S \qquad \rightarrow (10)$$

Where A_s is the dryer surface area (m^2) and S perimeter of the drying bin (m),

$$S = 2l + D$$

l is the thickness of the sample in dryer and D dryer diameter.

2.2.6. Determination of the effective moisture diffusivity:

In drying, diffusivity is used to indicate the flow of moisture within the material. In the falling rate period of drying, moisture transfer occurs mainly by molecular diffusion. Moisture diffusivity of the foods is influenced mainly by moisture content and also by their temperature.

Fick's second law of diffusion is often used to describe a moisture diffusion process **(crank, 1975):**

$$\frac{\partial m}{\partial \phi} = D_{eff} \cdot \nabla^2 m_{lo} \qquad \rightarrow (11)$$

Where m_{lo} is the local moisture content (dry basis), □ time (s) and D_{eff} effective moisture diffusivity (m^2/s).

In most situations, the food product is assumed as:

Moisture is initially uniformly distributed throughout the mass of sample, mass transfer is symmetric with respect to the center, surface moisture content of sample instantaneously reaches equilibrium with the condition of surrounding air, resistance to the mass transfer at the surface is negligible compared to internal resistance of the sample, mass transfer is by diffusion only and diffusion coefficient is constant and shrinkage is negligible.

The solution of Fick's equation for an infinite slab is as follows:

$$MR = \frac{M_t - M_e}{M_o - M_e} = \frac{8}{\pi^2} \exp\left(-\pi^2 F_o\right) \qquad \rightarrow (12)$$

Where: F_o Fourier number, $Fo = \frac{D_{eff} \cdot \phi}{L^2}$

L_{th} is the half-thickness of slab (m).

The previous equation can be rewritten as:

$$MR = \frac{8}{\pi^2} \cdot \exp\left(-\pi^2 \cdot Fo\right) \qquad \rightarrow (13)$$

$$\ln MR = \ln\left(\frac{8}{\pi^2}\right) - \left(\pi^2 \cdot Fo\right) \qquad \rightarrow (14)$$

$$Fo = -o.101 \ln MR - 0.0213 \qquad \rightarrow (15)$$

The effective moisture diffusivity (D_{eff}) was calculated using equation (16) as:

$$D_{eff} = \frac{Fo}{\left(\frac{\phi}{L_{th}^{2}}\right)} \rightarrow (16)$$

2.2.7. Compatibility of drying data to Lewis Newton's thin layer model:

Thin-layer model was applied to describe drying process of various products and drying methods. Several thin layer drying models are available in the literature for explaining drying characteristics of fruits and vegetables.

The drying data, reported as moisture ratio (MR) versus drying time, were fitted for Lewis Newton model to experimental data by the direct least square method using SPSS 16.0 software. The drying model used in this study is of the form:

$MR = \exp(-k\phi)$ **(Sarsavadia et al., 1999)** → (17)

2.2.8. The specific energy consumption (SEC) and cost:

The specific energy consumption to evaporate water of materials in this study was calculated by dividing the input energy consumption kW.h/kg$_{\text{water removed}}$ by the removed water (w_w) kg.

$$\textit{The energy consumption} = (P_m \times t_{on}) + (P_a \times t_t) \rightarrow (18)$$

Where P_m is the microwave power (kW), P_a power of air heated (kW), t_{on} total time of microwave on (h) and t_t total time of drying (h).

By dividing the energy consumption by the water removed,

$$SEC\ (kW \cdot h / kg_{\text{water removed}}) = \frac{[(P_m \times t_{on}) + (P_a \times t_t)] \times (100 - m_f)}{A(m_i - m_f)} \rightarrow (19)$$

$$Cost\ (LE / kg_{\text{water removed}}) = SEC \times price\ of\ kW \cdot h \rightarrow (20)$$

2.2.9. Quality evaluation:

- Rehydration ratio:

Rehydration capacity is useful to determine how the dried product reacts with the moisture. The rehydration capacities of dried slices were evaluated by immersing 5g of dried samples in boiled distilled water. Samples were removed at regular time intervals (each 5 min.) and weighed until difference in successive weighing was insignificant. Rehydration ratio was calculated from the following equation (Gowen, et al., 2008):

$$\text{Re}\,hydration\ ratio = \frac{w_t - w_d}{w_d} \qquad \rightarrow (21)$$

Where w_t is the mass of rehydration sample at any time (g) and w_d mass of dried sample (g).

- Color:

The color difference of fresh product and dried product was evaluated using a color chart.

3. RESULTS AND DISCUSSION

3.1. Dimensional analysis and the prediction equation:

The relationship between $Pi1 = MR$ and $Pi2 = v.\phi / \lambda$ at various $Pi3 = P_u / P$ was fitted to exponential equation of the form:

$$Pi1 = \exp(-a\,Pi2) \qquad \rightarrow \qquad MR = \exp\left(-a\,.\frac{v.\phi}{\lambda}\right)$$

Table (2) showed parameter "a" in previous equation under various drying conditions.

Table (2): Parameter "a" under various drying conditions.

Air temperature (C)	Microwave power (W)	a	R^2
40	85	0.000220	0.966
	175	0.000430	0.750
	250	0.000700	0.974
	320	0.001000	0.970
50	85	0.000230	0.970
	175	0.000510	0.979
	250	0.000822	0.962
	320	0.001100	0.970
60	85	0.000281	0.963
	175	0.000534	0.977
	250	0.000850	0.960
	320	0.001200	0.967

The parameter "a" that depends on the values of Pi3 is shown in fig. (2), the best fitted relation was logarithmic equation of the form:

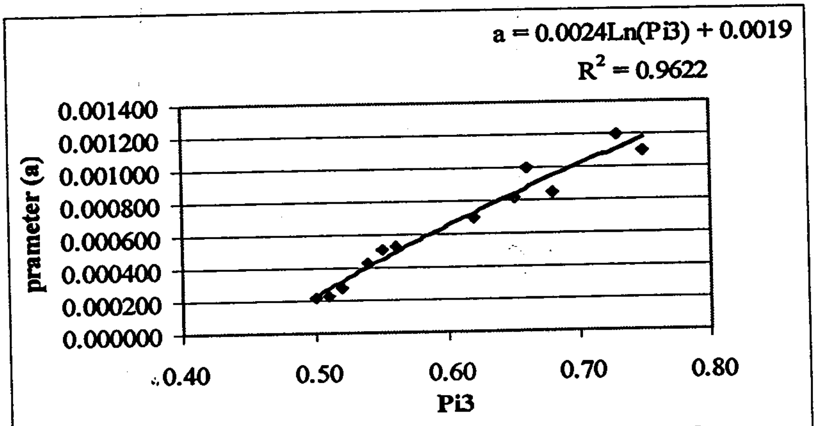


Fig. (2):The relation between prameter "a" and "Pi3".

$$a = 0.0023 Ln(pi3) + 0.0019$$

The general expression will be:

$$MR = \exp[-(0.0024 Ln(P_u / P) + 0.0019) \times (v \phi / \lambda)] \rightarrow (22)$$

R^2 ranged between 0.80 – 0.95.

Fig. (3) Shows the predicted and observed moisture ratio (MR).

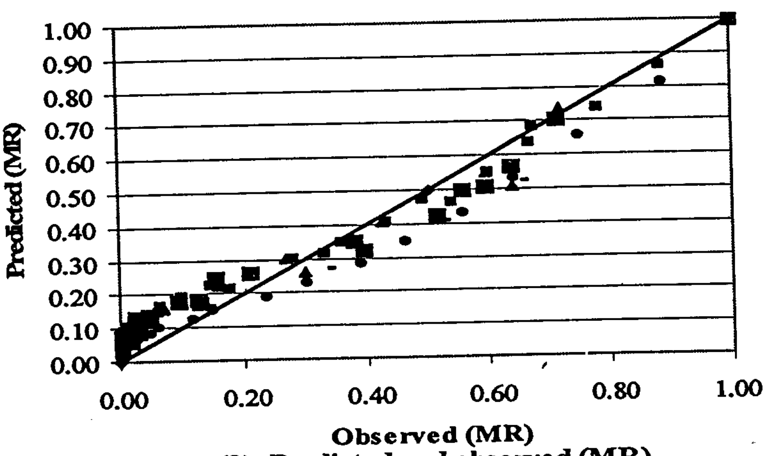
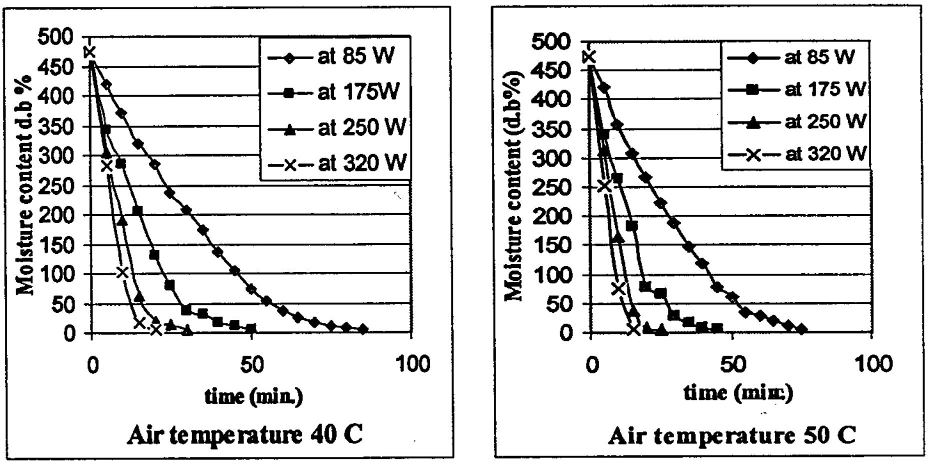


Fig. (3): Predicted and observed (MR).

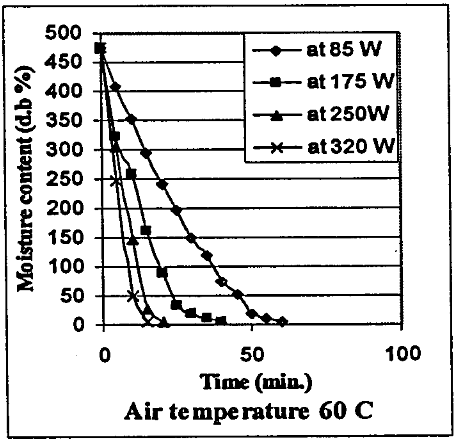
3.2. Effect of microwave power and air temperature on potatoes drying curves.

Experiments were carried out for microwave power (85, 175, 250 and 320 W) and air temperature (40, 50 and 60 °C) and air velocity 1.5 m/s as shown in fig. (4). It was found that the least drying time was with microwave power 320 W and air temperature 60 °C. The drying time for reducing initial moisture content of potatoes slices from 475% (d.b) to the final moisture contents of about 6% (d.b) with microwave powers of 85, 175, 250 and 320 were 85, 50, 30 and 20 min. for the air temperature of 40°C, 75, 45, 25 and 15 min. for the air temperatures 50 °C and 60, 40, 20 and 15 min. for the air temperature 60 °C respectively.



Air temperature 40 C

Air temperature 50 C



Air temperature 60 C

Fig. (4): Effect of microwave power and drying air temperature on drying time.

The drying rate of potato decreased with the decrease of moisture content and the average drying rate increased with the increase of microwave power level and air temperature at the same moisture content. In general, constant rate drying did not exist under any of test conditions, although high moist foods like potatoes can be expected to have a period of constant rate drying period; this was not observed in the present studies, probably because of the thin layer arrangement providing rapid drying conditions, in addition to rapid heating under microwave due to earlier observations of additional energy input, rapid heat penetration and forced expulsion of gases.

Fig. (5) shows the relation between total drying time and microwave power levels at air temperatures (40, 50 and 60 °C). Generally, it can be observed that the drying time decreased with increasing microwave power level and air temperature. This condition may be due to the rapid mass transfer of larger microwave heating power, because more heat is generated within the sample. Increased drying air temperature reduced the relative humidity of air, therefore increasing its ability to carry more water vapor out of the dryer.

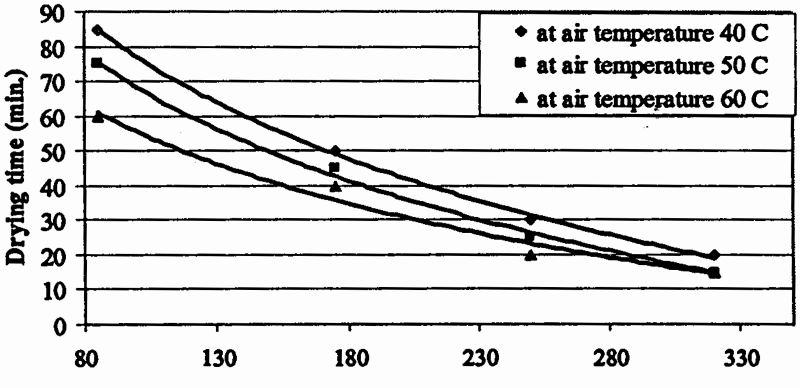


Fig.(5):Relation between the drying time and the microwave power at different air temperatures.

The relation between total drying time (t) and microwave power level (P) was as the following equation:

$$t = -a \ln(P) + b$$

The relation between parameter (a) and air temperature (T) was as the following equation:

$$a = 1099.2T^{-0.8308}$$

The relation between parameter (b) and air temperature (T) was as the following equation:

$$b = 6521.2T^{-0.8218}$$

The general equation between total drying time (t), microwave power level (p) and air temperature (T) for potatoes was of the form:

$$t = \left(-(1099.2T^{-0.8308}) \times \ln(P)\right) + \left(6521.2T^{-0.8218}\right) \rightarrow (23)$$

Fig. (6) shows the observed total drying time versus predicted drying time.

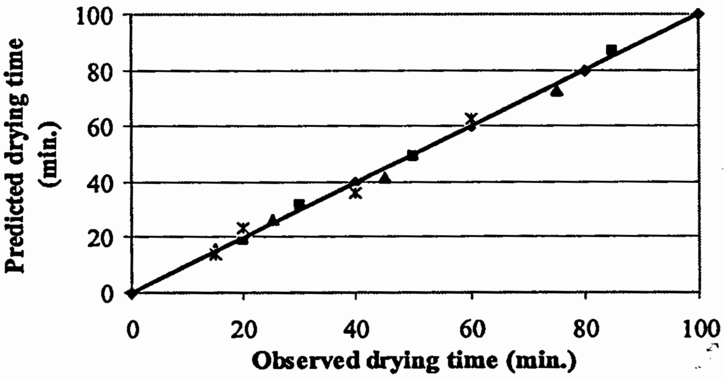


Fig.(6): Observed drying time versus predicted drying time at different microwave power level and air temperature.

3.3. Effect of microwave power and air temperature on average moisture diffusivity (D_{eff}) of potato:

The effective moisture diffusivity of food material characterizes its intrinsic mass transport property of moisture which includes molecular diffusion, liquid diffusion, vapour diffusion, hydrodynamic flow and other possible mass transport mechanisms. Table (3) shows the average effective moisture diffusivity at different microwave power and different air temperatures. Maximum values of the average effective moisture diffusivity (D_{eff}) 4.54×10^{-10}, 6.69×10^{-10} and 7.29×10^{-10} m^2/s were recorded at air temperatures 40, 50 and 60 °C respectively with the highest microwave power 320W, while the minimum values of (D_{eff}) 0.549×10^{-10}, 0.560×10^{-10} and 0.795×10^{-10} m^2/s were recorded at air temperatures 40, 50 and 60 °C with the lower microwave power 85 W.

Table (3): Effective average moisture diffusivity at different microwave powers and different air temperatures.

Effective average moisture diffusivity ($D_{eff} \times 10^{-10}$ m^2/s)					
Microwave power		**85W**	**175W**	**250W**	**320W**
Air temperature	**40 °C**	0.549	1.097	2.670	4.540
	50 °C	0.560	1.561	3.260	6.690
	60 °C	0.795	1.779	3.930	7.290

Generally, the effective moisture diffusivity values increased by decreasing in moisture content under all drying conditions, this agrees **Bouraoui, Richard and Durance (1994).** This may indicate that as moisture content decreased, the permeability to vapour increased, provided the pore structure remained open. The temperature of product rises rapidly in the initial stages of drying, due to more absorption of microwave heat. This increases the water vapour pressure inside the pores and results in pressure induced opening of pores. In the first stage of drying, liquid diffusion of moisture could be the main mechanism of moisture transport. As drying progressed further, vapour diffusion could have been dominant mode of moisture diffusion in the latter part of drying.

3.4. Compatibility of drying data to Lewis Newton model:

The drying data of microwave/convection drying system of potatoes as moisture ratio (MR) and the drying time were fitted to Lewis Newton model. Statistical analysis for Lewis Newton model showed that the coefficient of determination (R^2) of potatoes at different drying conditions in the present study varied between 0.754 and 1.00, reduced chi-square (X^2) varied between 0.00218 and 0.00739, root mean square error (RMSE) varied between 0.0467 and 0.0768 and modeling efficiency (EF) values varied between 0.958 and 0.981.

The complete prediction equation from Lewis Newton model for the moisture ratio takes the form:

$$MR = \exp(-(0.0000004T^{1.7135}) \times (P^{(2.3654T^{-0.2026})}) \times \phi) \qquad \rightarrow (24)$$

Figure (7) shows the observed moisture ratio versus predicted moisture ratio by previous equation at different microwave power levels and different air temperatures.

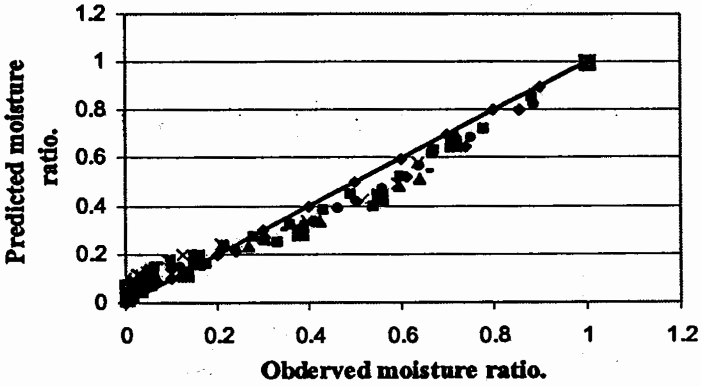


Fig. (7):Observed moisture ratio versus predicted moisture ratio by previous equation at different drying condition in this study.

3.5. Specific energy consumption and cost:

Energy consumption was determined in terms of specific energy consumption (SEC), kW.h / $kg_{water\ removed}$ as energy consumption per kilogram of water evaporated. The cost of water removed was determined by multiplying the (SEC) by the cost of kW.h assumed to be 0.25 LE / kW. h. The calculated (SEC) and costs at different microwave powers and different air temperatures for drying potato slices are shown in table (4).

3.6. Dried potato quality:

- Rehydration characteristics:

The rehydration of slices dried by microwave/convection dryer is affected by microwave power and air temperature. In all the cases, the amount of moisture absorbed increases with rehydration time, and then decreases to reach the saturation level. The rehydration stabilized in about

10 min. and the rehydration ratio was in the range of 2.19 – 3.41 under various drying conditions. Rehydration properties were improved by drying at higher microwave power indicating higher values of rehydration ratio. This may be due to; quick microwave energy absorption that causes rapid evaporation of water, creating a flux of rapidly escaping vapour which helps in preventing shrinkage and case hardening, thus improving the rehydration characteristics.

Table (4): Specific energy consumption and cost of water evaporated at different microwave powers and different air temperatures for potato slices.

Air temperature (C)	Microwave power (W)	SEC kW/kg	Costs LE/kg
40	85	0.76	0.19
	175	0.88	0.22
	250	1.04	0.26
	320	1.14	0.28
50	85	0.91	0.23
	175	0.95	0.24
	250	1.12	0.28
	320	1.21	0.30
60	85	0.94	0.24
	175	0.99	0.25
	250	1.14	0.29
	320	1.28	0.32

- Color:

There is no significant change in color when compared to the color of dried potato to compared with fresh potato where both the fresh potato and dried potato were of the same color number (5Y919 Yellow). Microwave power 250 and 320 W caused a charring in some dried potatoes slices, but microwave power 85 and 175 W did not cause any charring.

4. CONCLUSION

The aim of the present study is modeling a developed microwave/convection dryer using similitude analysis for drying a thin layer of potato (**Solanum Tuberosum**) slices, which can be helpful in design and operation criterion of this developed thin layer dryer type for drying other agricultural products. Drying time was affected by microwave power and drying air temperature, effective diffusivity "D_{eff}", compatibility of experimental data to Lewis Newton's thin layer drying model and rehydration and color as quality indicators were also studied. Four different levels of microwave power, namely: 85, 175, 250 and 320 W, three different drying air temperatures of drying air are 40, 50 and 60°C with air velocity of 1.5 m/s were studied.

Results indicate the following:

- The drying rate of potato slices decreased with decrease in moisture content, and the average drying rate increased with the increase of microwave power level and air temperature at the same moisture content.

- The effective moisture diffusivity values increased with decrease in moisture content under all drying condition.

- The general prediction equation of the moisture ratio of thin layer drying of potato slices using similitude analysis was of the form:

$$MR = \exp\left[-\left(0.0024\,Ln(P_u / P) + 0.0019\right) \times (\nu\phi / \lambda)\right]$$

R^2 varies between 0.8 - 0.95.

- Lewis Newton model for the moisture ratio was highly compatible with the experimental data.

$$MR = \exp(-(0.0000004\,T^{1.7135}) \times (P^{(2.3654\,T^{-0.2026})}) \times \phi)$$

R^2 varies between 0.75 – 1.00.

- The average Specific energy consumption and cost were (1.03 kW.h/kg$_{water}$) and (0.26 LE/kg$_{water}$) respectively at any drying conditions in this study.

- The rehydration ratio was in the range of 2.19 – 3.41 under various drying conditions. There was no significant change in color when compared to the color of dried potato compared to fresh potatoes, where both the fresh potatoes and dried potatoes had the same color number (5Y919 Yellow).

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الملخص العربى

نمذجة مجفف ميكروويف/حمل لتجفيف شرائح البطاطس

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- تهدف هذه الدراسة إلى نمذجة فرن ميكروويف مطور ليلائم تجفيف شرائح البطاطس فى طبقات رقيقة حيث يمكن لهذا النموذج أن يسهم فى تجفيف منتجات أخرى زراعية. ودراسة العوامل المؤثرة على التجفيف واستنتاج معادلة تربط بين المتغيرات التى يمكن أن تؤثر فى عملية التجفيف بهذه الطريقة من خلال التحليل البعدى للمتغيرات. أيضا تم دراسة مدى توافق النتائج التجريبية مع صيغة Lewis Newton وإيجاد ثوابت التجفيف لهذه الصيغة. كما تم تقييم جودة المنتج المجفف من خلال بعض الاختبارات كإختبار التشرب واللون للمنتج المجفف.

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- تم دراسة تأثير أربع قدرات للميكروويف (٨٥ , ١٧٥, ٢٥٠, ٣٢٠ وات) وثلاث درجات حرارة للهواء (٤٠, ٥٠, ٦٠ م°) عند سرعة هواء ١,٥ م/ث.

ويمكن تلخيص أهم النتائج التى تم التوصل إليها على النحو التالى:

- أقل زمن للتجفيف شرائح البطاطس تم الحصول عليه عند قدرة ميكروويف ٣٢٠ وات ودرجة حرارة هواء ٦٠ م°.

- قيم الإنتشار الرطوبى إزدادت مع الانخفاض فى المحتوى الرطوبى أثناء عملية التجفيف تحت ظروف التجفيف المختلفه لهذه الدراسة.

- تم التوصل الى نموذج رياضى باستخدام التحليل البعدى للتنبوء بقيم moisture ratio عند ظروف التجفيف المختلفه حيث حقق الصورة:-

$$MR = \exp\left[-\left(0.0024 Ln(P_u / P) + 0.0019\right) \times (v\phi / \lambda)\right]$$

وتراوحت قيم R^2 فيما بين ٠.٨٠ و ٠.٩٥

- تبين توافق صيغة Lewis Newton مع النتائج التجريبية والتى تربط بين قدرة الميكروويف Pودرجة حرارة الهواء T وmoisture ratio حيث كانت على الصورة:

$$MR = \exp(-(0.0000004\ T^{1.7135}) \times (P^{(2.3654\, T^{-0.2026})}) \times \phi)$$

وتراوحت قيم R^2 فيما بين ٠.٧٥ و ١.٠٠

- كان متوسط استهلاك الطاقة (1.03 كيلووات ساعة/كيلوجرام ماء مزال) ومتوسط التكلفة (٠.٢٦ جنيه/كيلوجرام ماء مزال) فى كل حالات الدراسة.

- أثناء اختبار التشرب لشرائح البطاطس المجففه إزدادت قيم الرطوبة الممتصة مع زيادة الزمن حتى تم تشبعها. وثبتت قيم التشرب بعد عشر دقائق تقريبا وتراوحت قيم نسب التشرب من ٢.١٩ إلى ٣.٣١ تحت مختلف ظروف التجفيف فى هذه الدراسة.

- لايوجد تغير يذكر فى لون شرائح البطاطس المجففه عن لون الشرائح الطازجة، حيث أن كلا من الشرائح الطازجة والمجففه كان لها نفس رقم شريحة اللون (*5Y919Yellow*) وقد تبين وجود احتراق فى بعض شرائح البطاطس المجففه عند استخدام قدرتى الميكروويف ٢٥٠ و ٣٢٠وات, أما عند استخدام قدرتى الميكروويف ٨٥ و١٧٥ وات فلم يوجد اى احتراق فى الشرائح المجففة.