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Experimental investigation of drying kinetics of apple with hot air, microwave and ultrasonic power

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Abstract. The experiments were performed for various conditions at 40–60 °C air temperature, 0.5–1.5 m/s air velocity, 120–600 W microwave and 50–200 W ultrasonic power so as to investigate the effects of drying air temperature, air velocity, microwave and ultrasonic power on the drying characteristics of apple slices. In the study, the combined use of hot air, microwave and ultrasonic energy for apple slices was determined as the most effective and fastest drying method. Besides, according to the experimental results applied to the models selected from the literature, the model that best described the drying characteristics of the apple under the microwave and ultrasonic effect was that of Midilli *et al* and the correlation coefficient R^2 was calculated to be between 0.9969 and 0.9999.

Keywords. Microwave drying; ultrasonic power; apple drying; modelling; drying kinetics.

1. Introduction

Food drying for storage is one of the oldest methods of preserving food [1]. A wide variety of machines have been produced by the techniques developed to date instead of classical drying methods, which are influenced by external factors. The most important input providing simultaneous heat and mass transfer in the drying process is the energy and the transfer mechanism of this energy. For this reason, a wide range of heat transfer mechanisms have been developed and applied to the machines to dry the products effectively and to have features on demand.

Although there are a wide variety of drying techniques (hot air, vacuum, freezing, spray, etc.) [2], the most widely used technique is hot air drying. In this drying technique, any energy input is used to heat the drying air, and this air with increased temperature and decreased relative humidity is sent to the product to be dried. In recent years, especially due to the fact that hot air drying costs much and it does not give the desired quality, some drying techniques have been developed to use different techniques alone or in combination. Microwave and ultrasonic drying techniques are the most important of these methods.

Microwave energy is used for internal heat generation by vibrating water molecules with high-frequency electromagnetic radiation [3]. This heat generation method provides a much faster and effective temperature increase than heat transfer by conventional heat transfer mechanisms. Ultrasonic sound waves can be defined as high-frequency pressure propagation. These high-frequency pressure vibrations accelerate heat and mass transfer because of the fact that they both increase the amount of air coming into contact with the product and facilitate the displacement of moisture by vibrating the water molecules in the substance [4, 5].

Apple fruit (*Malus domestica*) is commercially grown in many regions in Turkey and is dried and intensively used, especially in fruit crisp and fruit flour production in recent years. In the literature there are studies including several kinds of fruit and vegetables, taking into account the hot air, microwave and ultrasonic effect and investigating drying characteristics. Furthermore, a wide variety of drying models have been developed according to the assumption that the drying takes place in the drying zone at a constant and decreasing rate due to the short duration of the heating phase in the drying process. Five models applied to the experimental data from these models are given in table 1.

In the literature, there are theoretical and experimental studies on the drying characteristics of apple fruit and its drying process by different methods. Ullah and Kang [11] investigated the drying characteristics and collector performance of the apple by changing the flow of hot air obtained from the parabolic solar collector. Zlatanovic *et al* [12] dried apple cubes at low temperature with hot air flow. In the experiments, temperature changed between 35 and 55 °C, relative humidity changed between 10% and 30% and air velocity between 1 and 2 m/s. They applied the

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Table 1. Drying models in the literature.

Model name	Model	References
Newton	MR = $\exp(-kt)$	Ayensu [6]
Page	MR = $\exp(-kt^n)$	Diamente and Munro [7]
Logarithmic	MR = $a \exp(-kt) + c$	Yaldiz and Ertekin [8]
Wang and Singh	MR = $1 + at + bt^2$	Wang and Singh [9]
Midilli *et al*	MR = $a \exp(-kt^n) + bt$	Midilli *et al* [10]

drying data to the various models they selected from the literature and stated that Henderson and Pabis was the most suitable drying model for apple cubes [13]. Djekic *et al* [14] performed an experimental study on supercritical CO_2, hot air and freeze drying and comparison of shelf life of the apple. It was stated that supercritical CO_2 was the most effective method in the tests and there were some differences in comparing the packaging method and drying technique in terms of shelf life and quality parameters. In another study, Sturm *et al* [15] investigated the drying kinetics, colour and shrinkage properties of process control in hot air drying. The results indicated that the process method was not only effective in starting and ending the drying or in adjusting the temperature, but also it was very effective on colour change and shrinkage. Fonteles *et al* [16] experimentally investigated the effect of ultrasonic pretreatment on drying kinetics and product quality. This study showed that ultrasonic effect accelerated water diffusion within the product and thus accelerated drying. Cuccurullo *et al* [17] checked the product temperature in their study and they performed microwave drying. In their work, they chose the temperature as 60, 70 and 80 °C, and stated that temperature control in microwave drying had a serious effect on drying time.

When looking at the literature, it is seen that hot air, microwave and ultrasonic effects are examined alone, or, among these methods, hot air and microwave or hot air and ultrasonic pretreatment are combined together. Therefore, the combined use of hot air, microwave and ultrasonic power has never been studied before. This triple combination was investigated in terms of drying kinetics and efficiency and it was found to be the most effective drying method. In addition, the obtained data were applied to drying models, and drying model results and correlation coefficients of drying methods in various combinations were obtained.

2. Materials and method

2.1 *Experimental set-up*

In order to determine the drying characteristics of apple fruit under hot air, microwave and ultrasonic power, a laboratory scale convective dryer with microwave and ultrasonic power units was designed and manufactured. A schematic view of the test set-up and the placement of the measurement elements are given in figure 1.

The testing set consists of a 250-W radial fan with fresh air intake, a 4-kW resistance heater, an 800-W microwave generator at 2450 MHz, a maximum-200-W ultrasonic generator and appropriate transducers at 20 kHz frequency. A 5-m long channel with 200 × 200 mm^2 square was selected in the experimental set-up design; 3-m long flow development distance is left after the heater. In this way, a uniform air flow was obtained in the drying zone. In the drying zone, a microwave is positioned at the back of the channel and an ultrasonic transducer from the upper side. Metal space reflectors are installed to prevent the reflection and coming out of the magnetic field after heater resistance and before exhaust port. In addition, the perimeter of the duct is insulated with 50-mm-thick insulation material and the heat loss is minimized.

To measure and control the air conditions, an air velocity, a temperature and a humidity sensors were installed. In the drying process, a digital scale was used to measure the amount of moisture removed from the product. All energy sources and measuring elements included in the experiment set were integrated into the plc system to control the drying conditions and log the measurement values via intervals. The features of the devices used in the system are given in table 2.

In the system, the air temperature and humidity sensors are positioned to measure from the fresh air intake, after the heater from the drying section and from the exhaust area, and the hot wire velocity sensor is positioned to measure the air velocity from the drying zone inlet. The devices used in the measuring system are protected from the microwave

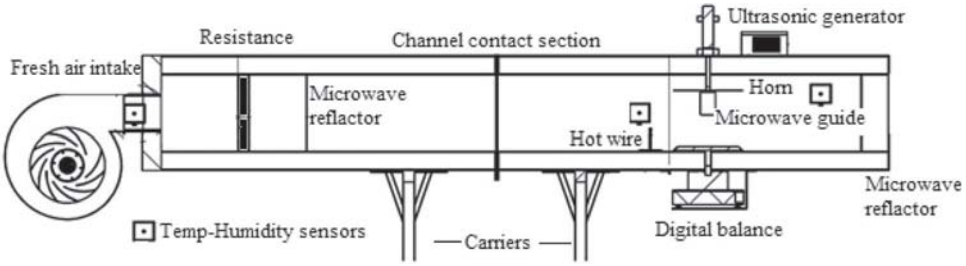

Figure 1. Microwave and ultrasonic-assisted convective dryer.

Table 2. Devices used in the experiments and their properties.

Device	Brand	Model	Range	Uncertainty
Digital balance	Dikomsan	Kd-Kc	0–300 g	±0.01 g
Moisture detector	Radwag	Mac-110	0–110 g	±1%
Digital anemometer	Kestrel	3500	0.1–60 m/s	±0.1 m/s
Hygrometer	Dixel	XH20 P	0–100%	±0.1%
Thermometer	Gemo	PT 100	0–400 °C	±0.1 °C

magnetic field by the Faraday cage. The wavelength was calculated as 120 mm and the sensors were protected with a suitable steel wire cage against wave leaks. Thus, the measuring sensors are protected from high-energy waves.

2.2 *Procedure of the experiments*

The apple fruits used in the experiments were maintained for 36 h at +4 °C and their physical and chemical properties were kept constant. The fruits taken from the cooler were maintained for 2 h in the ambient conditions before the experiments, and they were allowed to come to thermal equilibrium with the environment. Thus, similar starting conditions are provided for each experiment. For determination of the initial moisture content in the apple samples, a high-precision moisture measuring device (Radwag-Mac 110) with a halogen heater and with control and measurement properties was used. The mean initial moisture content for apple slices was 86.596% ± 0.10% according to the AOAC method on wet basis [18].

Before starting the experiments, the test set-up was operated idle until it reached the continuous regime on adjusting the energy source, temperature value and Microwave-ultrasonic power to be used through the plc system. Later, the samples with 2-mm thickness and about 50-g weight part were placed in circular trays and weight measurements were taken with 15-min intervals. The measurement was stopped when the weight difference between the last two measurements fell below 1.0% and the samples were considered to be dry. Each experiment was repeated three times under the same conditions and averaged. Finally, the change in moisture content was calculated and plotted based on the weight values by mathematical expressions.

2.3 *Mathematic formulation*

The moisture content of a material can be expressed in two ways according to the wet and dry basis and can be calculated as follows [19]:

$$M_{wb} = \frac{M_w}{M_w + M_d}, \tag{1}$$

$$M_{db} = \frac{M_w}{M_d}. \tag{2}$$

Moisture ratio (MR) of the product at any time during the drying can be calculated as follows [20, 21]:

$$\mathrm{MR} = \frac{M_t}{M_o}. \tag{3}$$

The moisture content change per unit time in the dried product is called the drying rate and is calculated by the following equation [22, 23]:

$$\mathrm{DR} = \frac{M_{t+\Delta t} - M_t}{\Delta t}. \tag{4}$$

The effective diffusion coefficient is calculated using D_{eff} (Eq. (5)). In this equation, ln(MR) is drawn as a function of time and the slope K is obtained [24, 25]:

$$K = \frac{\pi^2 D_{eff}}{4L^2}. \tag{5}$$

Activation energy (E_a) shows the energy required to remove 1 mol of water from the substance under certain drying conditions. The variation of the diffusion coefficient, depending on the drying air temperature, is basically defined by an Arrhenius-type function [26, 27]. If the effective diffusion coefficient from Eq. (5) is found and used in Eq. (6), the activation energy can be calculated:

$$D_{eff} = D_o \exp\left(-\frac{E_a}{RT_{abs}}\right). \tag{6}$$

Here, D_o is the diffusivity value for infinite moisture content (m^2/s). Taking logarithms of both sides of Eq. (6) yields a straight line variation as follows:

$$ln\left(D_{eff}\right) = ln\left(D_{o)}\right) - \frac{E_a}{RT_{abs}}. \tag{7}$$

Uncertainty analysis of the experimental study [28] was made and the total uncertainties of the parameters calculated for all working conditions are given in table 3.

3. Results and discussion

3.1 *Effects of drying air temperature on drying process*

Experiments were carried out at a constant 1.0 m/s air velocity at 40, 50 and 60 °C to investigate the effect of drying air temperature on the drying kinetics of apple slices. Moisture content according to dry basis in terms of time and drying rate according to moisture content are given in figures 2 and 3, respectively. It is seen in figure 2 that temperature rise increases the water vapour pressure on the product surface; thus, the drying rate also increases; however, this increase rate reduces after 50 °C. In the drying process, in order to evaporate the water from the surface at a certain rate, the moisture in the sample material

Table 3. Uncertainties of the calculated parameters.

Drying conditions	*T* = 40 °C *V* = 1.0 m/s	*T* = 50 °C *V* = 1.0 m/s	*T* = 60 °C *V* = 1.0 m/s	*T* = 50 °C *V* = 0.5 m/s	*T* = 50 °C *V* = 1.5 m/s	*T* = 50 °C *V* = 1.0 m/s MW = 120 W	*T* = 50 °C *V* = 1.0 m/s MW = 350 W	*T* = 50 °C *V* = 1.0 m/s MW = 600 W	*T* = 50 °C *V* = 1.0 m/s US = 50 W	*T* = 50 °C *V* = 1.0 m/s US = 100 W	T = 50 °C V = 1.0 m/s MW = 350 W US = 200 W
Parameter						Uncertainty					
Moisture content (db)	±0.0198	±0.0203	±0.0281	±0.0201	±0.0244	±0.0207	±0.0263	±0.0267	±0.0226	±0.0236	±0.0244
Moisture ratio	±0.0237	±0.0247	±0.0314	±0.0211	±0.0277	±0.0199	±0.0295	±0.0241	±0.0269	±0.0247	±0.0282
Drying rate	±0.0019	±0.0021	±0.0028	±0.0025	±0.0027	±0.0024	±0.0021	±0.0023	±0.0023	±0.0024	±0.0026

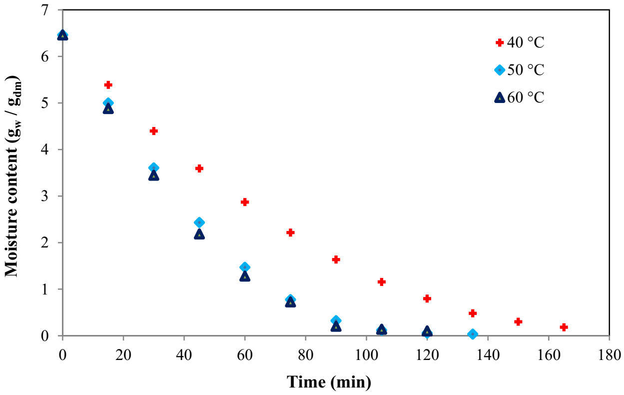

Figure 2. Variation of moisture content with time.

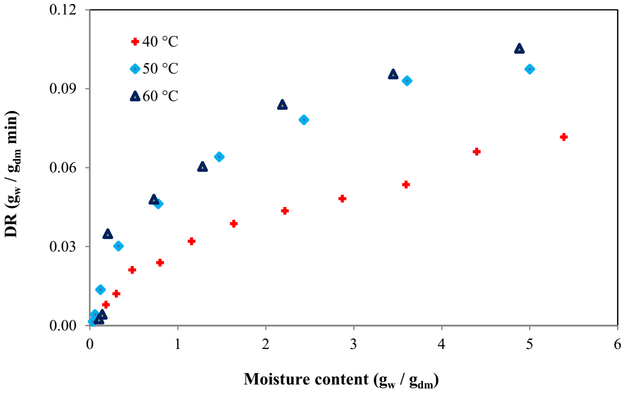

Figure 3. Variation of drying rate with moisture content.

must diffuse from the substance to the surface at the same rate as the evaporation rate. However, when the surface evaporation rate increases above 50 °C, the moisture diffusion rate in the product remains below the evaporation rate. This leads to a decrease in drying rate as water cannot be transferred to the surface in sufficient quantities.

It is seen that there is a similar situation in figure 3. In addition, the decrease in the amount of moisture in the product caused a decrease in the drying rate as well. This is due to a decrease in the amount of bound moisture in the product and due to the slowing of internal diffusion in the substance.

The diffusion coefficients and the calculated activation energy at different drying air temperatures are given in table 4. When the table is examined it is seen that the temperature increase from 40 to 50 °C causes a 28% increase in the diffusion coefficient, while an increase of 15% occurs from 50 to 60 °C. This shows that the increase in diffusion coefficient with temperature is not linear and the physical properties of the substance are predominant in moisture diffusion. Activation energy is calculated by the Arrhenius-type relation shown in figure 4 depending on the effective diffusion coefficient and absolute temperature. The activation energy was found to be 31.741 kJ/mol in the

Table 4. Effective diffusion coefficient at different temperatures and activation energy for determined apples.

$E_a \left(\frac{\text{kJ}}{\text{mol}}\right)$	$D_{eff} \times 10^{10}$ (m^2/s) 40 °C	50 °C	60 °C
31.741	2.431	3.115	3.582

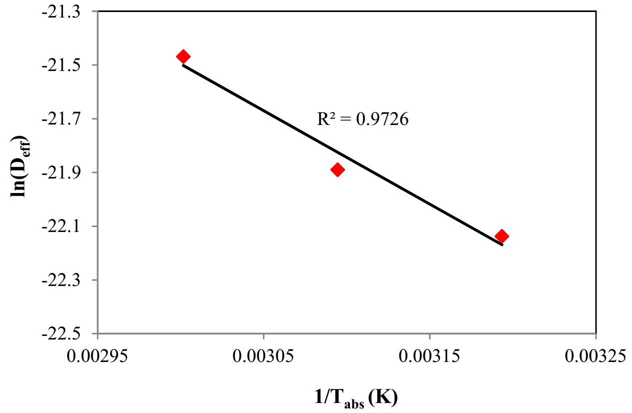

Figure 4. Arrhenius-type relationship between the effective diffusivity of the apple slices and reciprocal absolute temperature.

calculation here. According to Zogzas *et al* [29], the activation energy for agricultural products varies between 12.7 and 110 kJ/mol.

3.2 *Effects of drying air velocity on drying process*

Experiments were carried out at a constant temperature of 50 °C at 0.5, 1.0 and 1.5 m/s air velocity to examine the effect of drying air velocity on drying kinetics. In figures 5 and 6, moisture content changes according to dry basis with time and drying rate with moisture content are given. When the graphs were examined, it was seen that the drying air velocity affected the drying rate up to a certain level and the increase of air velocity after this velocity value had little effect on the drying. More heat is transferred to the product on increasing the rate of drying air, thus increasing the evaporation from the surface. However, the same amount of water must be diffused from inner region of the material to the surface in order to increase the drying rate. Therefore, when the rate of drying air rises above a certain value, diffusion from internal material to the surface is insufficient; this reduces the increasing of drying rate. Thus, the amount of water evaporating from the surface is limited by internal diffusion.

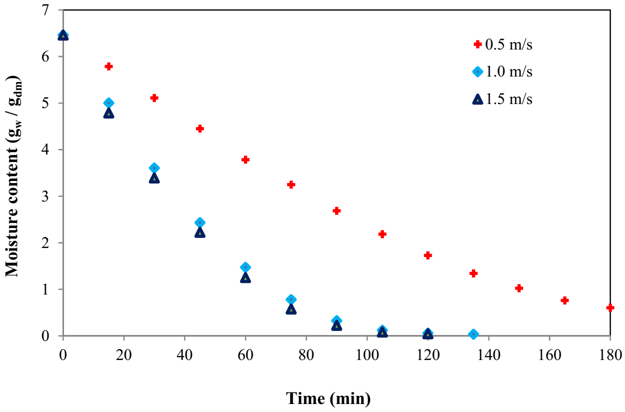

Figure 5. Variation of moisture content with time.

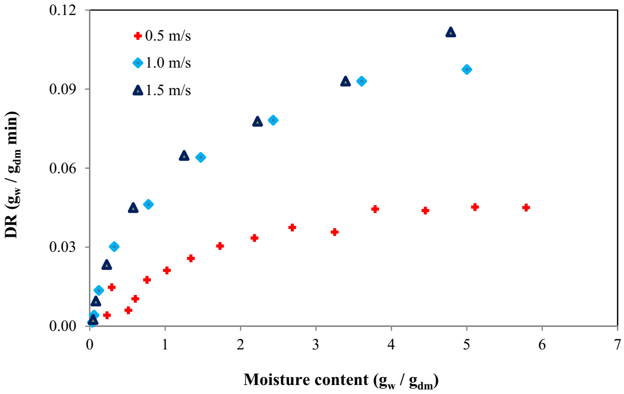

Figure 6. Variation of drying rate with moisture content.

Besides, in diffusion calculation for 0.5, 1.0 and 1.5 m/s velocities of drying air, 1.474×10^{-10}, 3.115×10^{-10} and 3.234×10^{-10} m^2/s were obtained, respectively. When the diffusion coefficient values were considered, the increase in air velocity from 1.0 to 1.5 m/s resulted in a change of 3.2% on moisture diffusion.

3.3 *Effects of microwave power on drying process*

To investigate the effects of microwave energy with different powers on the drying kinetics, experiments are conducted at 120, 350 and 600 W microwave power at 50 °C temperature and 1.0 m/s air velocity value of the drying air, and the change in the moisture content over time and the change in the drying rate with moisture content are given in figures 7 and 8, respectively. In figure 7, it is observed that increasing the microwave power from 120 to 350 W decreases the drying time by 3 times and the increase to 600 W decreases it by 6 times. Internal heating by rubbing of atoms together at high speeds due to microwave energy and therefore internal heat generation gives rise to temperature increase and this local temperature increase increases the vapour pressure; thus this mechanism has a big effect on drying kinetics.

In addition to this, when figure 8 was examined for the effects of microwave energy on drying rate values, it was seen that when the moisture content was high, the drying rate was also high due to high heat generation with

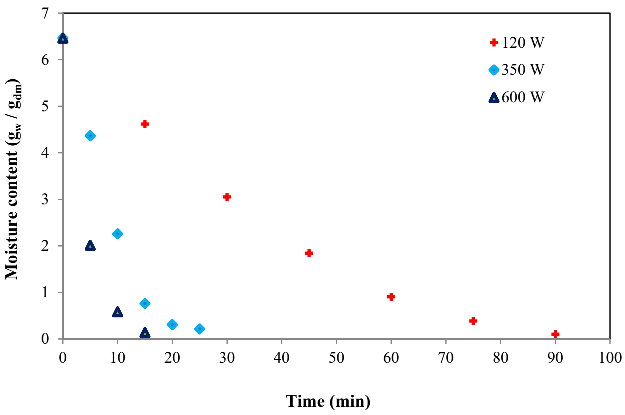

Figure 7. Variation of moisture content with time.

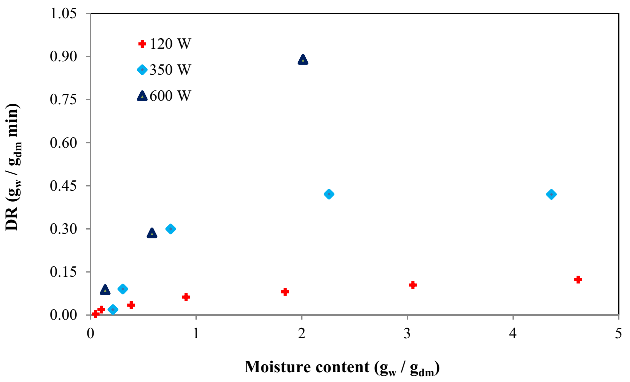

Figure 8. Variation of drying rate with moisture content.

microwave. With the rapid decrease in moisture content drying rate rapidly decreases as well, and drying rate rises with increasing microwave power density.

Diffusion coefficients for microwave energy at different powers were obtained as 3.451×10^{-10}, 5.489×10^{-10} and 9.765×10^{-10} m^2/s for 120, 350 and 600 W, respectively. When these values were compared with convective heating only, it was seen that there was a 3 times diffusion coefficient increase with 600-W microwave power.

3.4 *Effects of ultrasonic power on drying process*

To examine the effect of ultrasonic pressure distribution on drying characteristics, ultrasonic sound wave energy of 50 and 100 W is applied at a constant air temperature of 50 °C, and the results are given in figures 9 and 10 as change of moisture content over time and change in drying rate with moisture content, respectively, without ultrasonic effect and with 50 and 100 W ultrasonic effect. When figure 9 was examined, it was seen that the water in the product was vibrated at high frequency with the ultrasonic sound wave energy; breakdown of moisture in material and the diffusion of the water molecules in the apple was accelerated; thus the drying rate enhanced with the increase of water transfer from interior to the surface. Figure 10a shows that the effect of ultrasonic vibration is more effective on the drying rate in the case of high moisture content, and increasing ultrasonic power positively affects the drying rate.

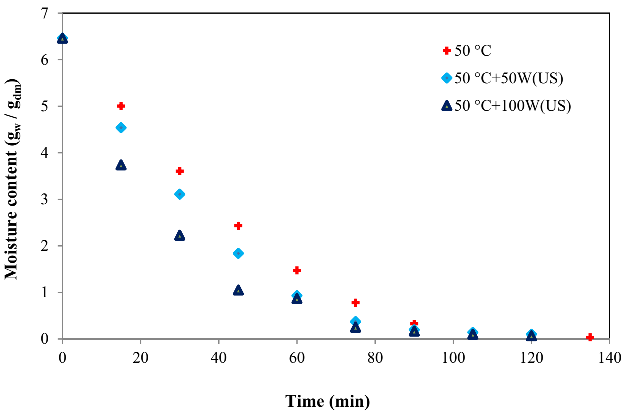

Figure 9. Variation of moisture content with time.

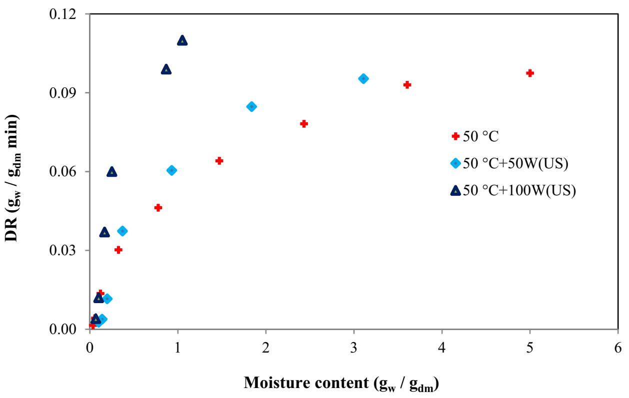

Figure 10. Variation of drying rate with moisture content.

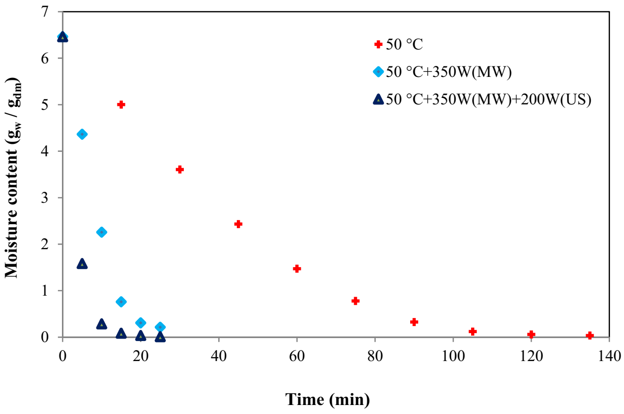

Figure 11. Variation of moisture content with time.

In the experiments carried out under ultrasonic effect, 50-W pressure diffusion energy increased diffusion

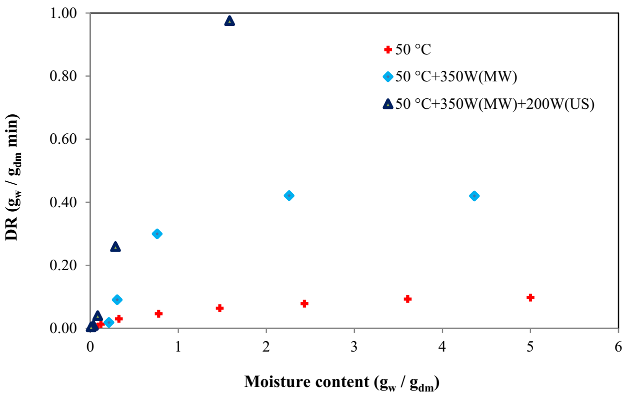

Figure 12. Variation of drying rate with moisture content.

Table 5. Coefficients and statistical data for various microwave powers of apple drying.

T = 50 °C, *V* = 1.0 m/s Model		Microwave power 120 W	 350 W	 600 W
Newton	R^2	0.9698	0.9877	0.9911
	RMSE	0.03223	0.01347	0.01674
	k	0.02895	0.03678	0.03897
Page	R^2	0.99801	0.9897	0.9917
	RMSE	0.03457	0.01347	0.01299
	k	0.05163	0.04174	0.05185
	n	0.8211	0.9781	0.9340
Wang and Singh	R^2	0.9835	0.9896	0.9851
	RMSE	0.02201	0.03381	0.07041
	a	−0.01024	−0.02547	−0.02589
	b	0.0001911	0.0001385	0.0001792
Logarithmic	R^2	0.9932	0.9987	0.9911
	RMSE	0.01141	0.007784	0.006012
	a	0.9345	0.9897	0.9587
	c	0.05897	0.02987	0.03541
	k	0.03486	0.04001	0.04891
Midilli *et al*	R^2	0.9978	0.9997	0.9990
	RMSE	0.01078	0.003474	0.006889
	a	1.023	1.0012	0.9978
	b	0.000325	0.000389	0.000374
	k	0.03982	0.03123	0.04089
	n	0.9129	1.1130	0.9897

Table 6. Coefficients and statistical data for various ultrasonic powers of apple drying.

T = 50 °C, *V* = 1.0 m/s Model		Ultrasonic power –	 50 W	 100 W
Newton	R^2	0.9647	0.9874	0.9897
	RMSE	0.03981	0.01487	0.01861
	k	0.02847	0.03687	0.03827
Page	R^2	0.9801	0.9932	0.9941
	RMSE	0.03963	0.01412	0.01258
	k	0.05102	0.04321	0.05478
	n	0.8345	0.9693	0.9098
Wang and Singh	R^2	0.9905	0.9841	0.9789
	RMSE	0.02421	0.03985	0.07363
	a	−0.01134	−0.02389	−0.02547
	b	0.0001801	0.0001374	0.0001547
Logarithmic	R^2	0.9894	0.9971	0.9981
	RMSE	0.01012	0.008421	0.005342
	a	0.9381	0.9645	0.9598
	c	0.05824	0.02985	0.03457
	k	0.03241	0.03851	0.04189
Midilli *et al*	R^2	0.9969	0.9997	0.9998
	RMSE	0.01141	0.005732	0.005941
	a	1.019	0.9819	0.9914
	b	0.0002752	0.000441	0.0003392
	k	0.04066	0.03279	0.04249
	n	0.9237	1.0496	0.9973

coefficient from 3.115×10^{-10} to 3.845×10^{-10} m^2/s and the diffusion coefficient reached $5.753x10^{-10}$ m^2/s when the applied ultrasonic power was increased to 100 W. The doubling of ultrasonic power increased the diffusion coefficient by 34.56%.

3.5 *Effects of combined microwave and ultrasonic power on drying process*

To investigate the effects of microwave, ultrasonic and combined hot air drying technique on drying kinetics, experiments were carried out with only hot air, hot air and microwave, hot air microwave and ultrasonic power at 50 °C, 1.0 m/s air velocity and 350 W microwave power and 200 W ultrasonic power. The results obtained from these experiments are shown in figures 11 and 12 as the change of moisture content over time and the change in drying rate with moisture content, respectively. When figure 11 was examined it was seen that the use of microwave energy and internal heat production, as well as the convective heat transfer of the outer surface of the product, increased the temperature quickly, with the warm up of the moisture within the product, before it rose to the surface, and this enhanced the pressure of surface moisture water vapour, so the drying accelerated. In addition, when the ultrasonic power was added to the hot air and microwave energy, the increase in the temperature of the water in the product made it easy to rise to the surface by vibrating and enhanced the drying rate remarkably. When figure 12 was examined, it was seen that both microwave and ultrasonic effect influenced drying much more, especially when the bound moisture in the target point product was high. With the reduction in moisture content, both the microwave and ultrasonic effect reduced and the drying rate decreased.

In the experiments carried out in hot air flow, microwave and ultrasonic effect, the addition of 350-W microwave energy increased the diffusion coefficient from 3.115×10^{-10} to 5.489×10^{-10} m^2/s while 200-W

Table 7. Coefficients and statistical data for various combined microwave and ultrasonic powers of apple drying.

T = 50 °C, V = 1.0 m/s		Microwave + ultrasonic power		
Model		–	350 W + –	350 W + 200 W
Newton	R^2	0.9647	0.9877	0.9915
	RMSE	0.03981	0.01347	0.01544
	k	0.02847	0.03678	0.03969
Page	R^2	0.9801	0.9897	0.9914
	RMSE	0.03963	0.01347	0.01041
	k	0.05102	0.04174	0.05261
	n	0.8345	0.9781	0.9452
Wang and Singh	R^2	0.9905	0.9896	0.9890
	RMSE	0.02421	0.03381	0.05985
	a	−0.01134	−0.02547	−0.03014
	b	0.0001801	0.0001385	0.0001947
Logarithmic	R^2	0.9894	0.9987	0.9989
	RMSE	0.01012	0.007784	0.007985
	a	0.9381	0.9897	0.9458
	c	0.05824	0.02987	0.03259
	k	0.03241	0.04001	0.04171
Midilli *et al* [10]	R^2	0.9969	0.9997	0.9993
	RMSE	0.01141	0.003474	0.006311
	a	1.019	1.0012	0.9998
	b	0.0002752	0.000389	0.0002791
	k	0.04066	0.03123	0.04892
	n	0.9237	1.1130	0.9874

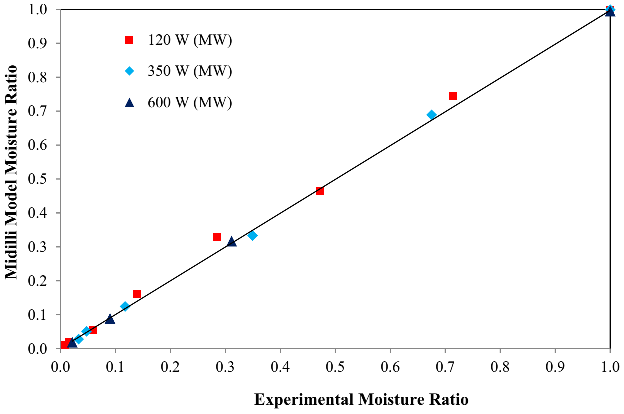

Figure 13. Variation of experimental results with Midilli *et al* model on microwave power.

ultrasonic power, applied additionally to the system, enhanced diffusion coefficient to 8.814 × 10^{-10} m^2/s.

3.6 *Comparison of drying behaviours of the apple with the drying models in the literature*

Moisture values obtained from experimental data with microwave and ultrasonic ranging power values for 50 °C constant temperature and 1.0 m/s constant air velocity were applied to five different models chosen from the literature by Matlab program. Non-linear regression analysis was used to estimate the parameters of those five models. The obtained model equation coefficients, correlation coefficient (R^2) and root mean square error (RMSE) values are given in tables 5, 6 and 7 for different drying conditions including microwave and ultrasonic power. The best model describing the thin-layer drying characteristics was chosen as the one with the highest R^2 values and the lowest RMSE values. According to the obtained data, the model most compatible with the experimental results is Midilli *et al* [10]; R^2 values range from 0.9969 to 0.9999 and RMSE value 0.01 and below.

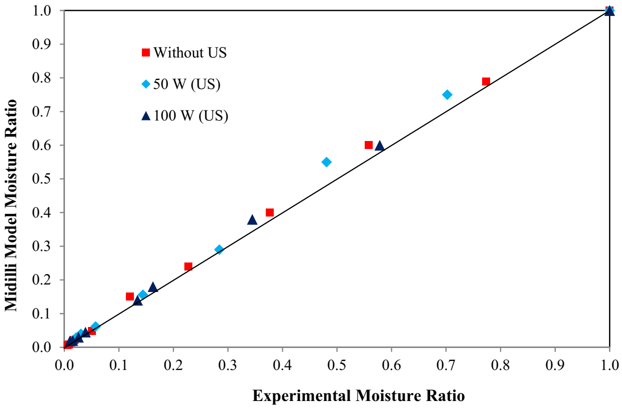

Figure 14. Variation of experimental results with Midilli *et al* model on ultrasonic power.

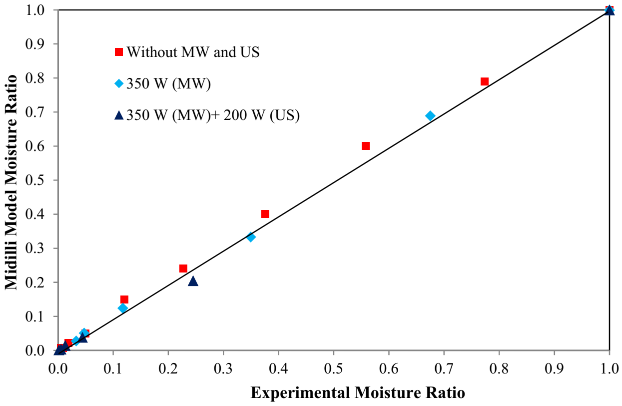

Figure 15. Variation of experimental results with Midilli *et al* model on combined microwave and ultrasonic power.

In figures 13, 14 and 15, the comparison of experimental results with model results is given. When these figures are examined, it is seen that the experimental results for all drying conditions are quite compatible with the model results.

4. Conclusions

The drying characteristics of apple slices at different drying air temperatures, air velocities, microwave and ultrasonic powers were studied experimentally. According to the data obtained from the experiments, the following conclusions were reached:

- High drying air temperature increases diffusion coefficient and hence drying rate increases. A similar effect was also seen when drying air velocity increased. However, it can be said that enhancing drying air velocity over 1.0 m/s does not cause a significant increase in drying rate.
- Activation energy was calculated as 31.47 kJ/mol for apple slices, while effective diffusion coefficients increased with temperature, air velocity and microwave and ultrasonic power. This result is also present in the literature.
- Drying rate was high for all experiments when moisture content was high but it decreased with decreasing moisture content. This reduction was more significant for microwave and ultrasonic power, which was particularly effective on the bound moisture in the product.
- On increasing the microwave power, the bound moisture temperature in the material increases rapidly; this enhances the surface vapour pressure and accelerates the drying very much.
- The application of ultrasonic pressure energy on the apple slices facilitated the rising of the bound moisture to the surface via vibration in the substance and caused a significant increase in drying rate.
- While decreasing drying stage was observed in all drying experiments, the most effective and fastest drying was obtained by triple combination of hot air, microwave and ultrasonic power. This is due to the increase in convective heat transfer with increasing temperature, the breakdown of moisture in material by ultrasonic pressure waves, the movement in internal structure with high-frequency vibrations and the internal heating by rubbing of atoms together at high speeds due to microwave energy and therefore internal heat generation.
- The experimental results were applied to five different models selected from the literature, and it was seen that Midilli *et al* model was the most compatible model according to the parameters selected for hot air, microwave and ultrasonic drying.

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Nomenclature

a, b, c	Constants of models
D_{eff}	Diffusion coefficient, m^2/s
D_o	Arrhenius factor, m^2/s
DR	Drying rate, g_w/g_{dm} min
E_a	Activation energy, kJ/mol
k	Drying rate constants in models, 1/min
K	Slope
L	Half the thickness of the thin layer slice, m
M_d	Mass of dry matter, g
M_o	Initial mass, g
M_w	Mass of wet matter, g
MR	Moisture ratio
n	Exponents in model equations
R	Universal gas constant, kJ/mol K
R^2	Correlation coefficient
RMSE	Root mean square error
RH	Relative humidity, %
t	Drying time, min
T	Temperature, °C
T_{abs}	Absolute temperature, K
V	Air velocity, m/s
Δt	Time, min

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