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Determination of Some Drying Parameters of Carrot Dried Using Microwave Method

Aytaç MORALAR, Soner ÇELEN*

Department of Mechanical Engineering, Namık Kemal University, 59860, Tekirdağ, Turkey.
*scelen@nku.edu.tr

Abstract: In this study, moisture content, drying time, the diffusion coefficient, activation energy, drying rate, drying efficiency and the energy consumed during the drying of carrot were determined by using the designed microwave supported conveyor drier. In the experiments, the carrot slices of 4 mm, 7 mm and 10 mm thickness were dried at a power of 1050 W, 1500 W and 2100 W microwave power. The conveyor drier has the conveyor speed of 0.245 m min^{-1} for drying process. At the end of drying process, it was found that the effective diffusivity coefficients, energy consumption, drying rate and drying efficiency have increased as the microwave power increased. We concluded that 1050 W is the optimum value for carrot drying in terms of drying time and energy consumption.

Keywords: Activation Energy; Diffusion Coefficient; Drying; Microwave Energy

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Mikrodalga Metodu Kullanılarak Kurutulan Havucun Bazı Kuruma Parametrelerinin Belirlenmesi

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Öz: Bu çalışmada nem içeriği, kuruma süresi, difüzyon katsayısı, aktivasyon enerjisi, kuruma hızı, kuruma etkinliği ve havucun kurutulması sırasında tüketilen enerji, tasarlanan mikrodalga destekli konveyör kurutucu kullanılarak belirlenmiştir. Deneylerde, 4 mm, 7 mm ve 10 mm kalınlığındaki havuç dilimleri, 1050 W, 1500 W ve 2100 W mikrodalga gücünde kurutuldu. Konveyör kurutucusu, kurutma işlemi için 0.245 m min^{-1} konveyör hızına sahiptir. Kurutma işleminin sonunda, mikrodalga gücü arttıkça efektif difüzyon katsayısı, enerji tüketimi, kuruma hızı ve kuruma verimliliğinin arttığı bulunmuştur. Kurutma süresi ve enerji tüketimi açısından havuç kurutma için 1050 W gücün en uygun değer olduğu sonucuna varılmıştır.

Anahtar kelimeler: Aktivasyon enerjisi; Difüzyon katsayısı; Kurutma; Mikrodalga enerjisi

1. Introduction

Carrot (*Daucus carota L.*) is one of the important vegetables belonging to umbelliferae family [1]. Carrots are grown in the Middle East and Central Asia for more than two thousand years. It was brought to Spain by Arabs thousands of years ago and then spread all over Europe and Africa [2]. The origin of carrot is Turkey. It is a vegetable consumed in every season throughout the world while they are produced as a winter vegetable in Turkey. It is also abundant in terms of vitamins A, B, C, D and E. It also contains carotene, sugar and phosphorus [3]. 100 grams of carrots contain 40 calories. Beta-carotene, found in the carrot, protects against vision loss due to aging. It helps digestion by making the intestines function well. It cleans blood by helping to remove harmful substances from the body. Dried carrots are used in pastries, salads, soups and sauces [4, 5].

The method of keeping the foods by drying is the oldest keeping method the mankind have learned from nature and have been using since the ancient history [6]. Since the amount of water in the food is reduced by the drying process, the possibility of enzymatic and microbiological deterioration is considerably reduced [7, 8, 9]. Above all, the current water in the food is reduced to a level that does not allow it to deteriorate. It is the cheapest method of storage. Low labour cost and the less equipment needs also reduces the costs. Dried products are rich in nutritional value and at the same time they are healthy and have taken their place both in the local and foreign markets as their transportation is easier when compared to fresh ones. Therefore, drying time and energy consumption of dryer is important in drying fruits in food sector [10].

During the drying process, heat is given to dry the product and the evaporation of the water is ensured. The water evaporates from the outer surface of the material. The drying takes place in this way. As the temperature difference between the temperature of the drying air and the temperature of the material increases, so does the heat transfer rate.

There are many types of dryers in the world due to the fact that drying takes place in many areas of the industry [11]. In recent years, due to its advantages such as low drying time, homogeneous heat distribution, good product quality and low energy consumption, drying with microwave energy instead of hot air drying has been investigated [7, 12].

In recent years, paralel to technological improvements, the microwave applications are widely studied among processes used to make food durable or consumable. Microwaves are parts of the electromagnetic spectrum and are located between visible light and radio waves. Wave length ranges from 10-3 m to 1 m and frequencies range from 0.3 GHz to 300 GHz [13]. Microwave drying differs markedly from conventional drying methods. In conventional drying, due to the temperature difference between the hot surface and the colder interior, a gradual transmission of heat from the surface of the material towards the interior part is observed [6]. Microwave drying is an alternative drying method which provides advantages in terms of providing high heat conduction to the internal parts of the dried material, cleaning, energy gain, easy process control and the quick start and termination of the drying process [14]. Compared to conventional heating methods, microwave heating has advantages such as rapid heating, volumetric heating, and an easy-to-control heating process [15, 16].

The mechanism of moisture movement within the materials is shown by effective moisture diffusivity. In the drying process, the diffusivity is assumed to be water diffusion to the surface of the material. Knowing the diffusion coefficient in fluid mechanics and mass transfer processes provide convenience in their design. The drying of most of the nutrients takes place at the second stage of drying processes, which is the falling rate period, and the moisture transfer during the drying is controlled by internal diffusion [17].

Diffusion coefficient has been studied in drying of some products [4, 14]. Different dryers have been used in the drying of the carrot. These studies are; microwave vacuum drying [12], conveyor drying [4], electric and infrared drying [18], air impingement drying [19] and solar drying [20].

In this study, the carrot slices were aimed to be dried by using microwave energy on the conveyor with the dimensions of 3.5x0.5x0.4 m on the plot scale that we have designed. The experiments are conducted with different powers, different slice thickness and constant belt speed to compare their energy consumption at the end of the drying in order to show the usability of the microwave energy.

2. Materials and Methods

2.1. Materials

In this study, carrots (*Daucus carota L.*) with $7.62 \pm 0.5\%$ (dry base), sliced 4 mm, 7 mm and 10 mm, were bought from the local market kept at 4 ^{o}C were used (as seen Fig. 1). As only 1050 W power value was recommended as the result of the experiments, only the photos of carrots dried at this power value were given.
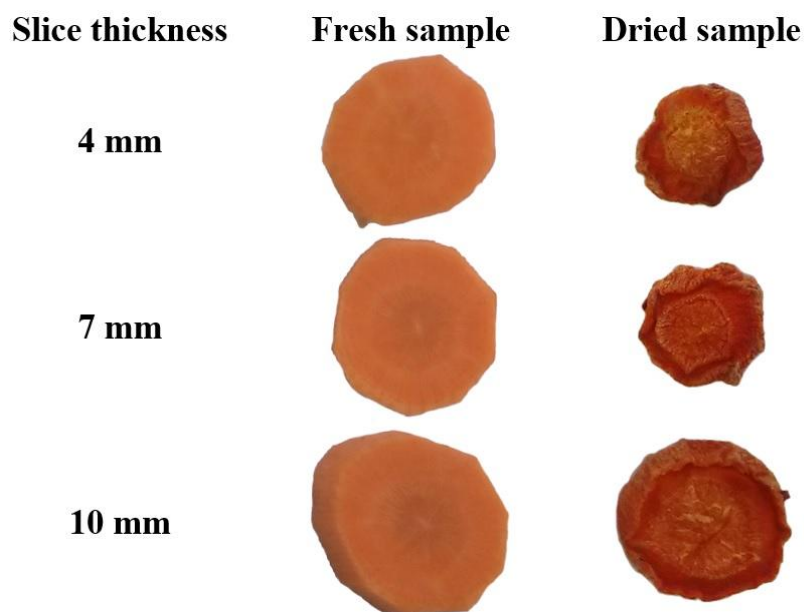

Figure 1. Pictures of the carrot slices at 1050 W.

2.2. Drying Tests

Drying experiments were carried out at the microwave power of 1050 W, 1500 W and 2100 W (maximum 2100 W, 2.450 GHz) at band speed of 0.245 m min^{-1} without any pretreatment of the carrot (as seen Fig. 2).
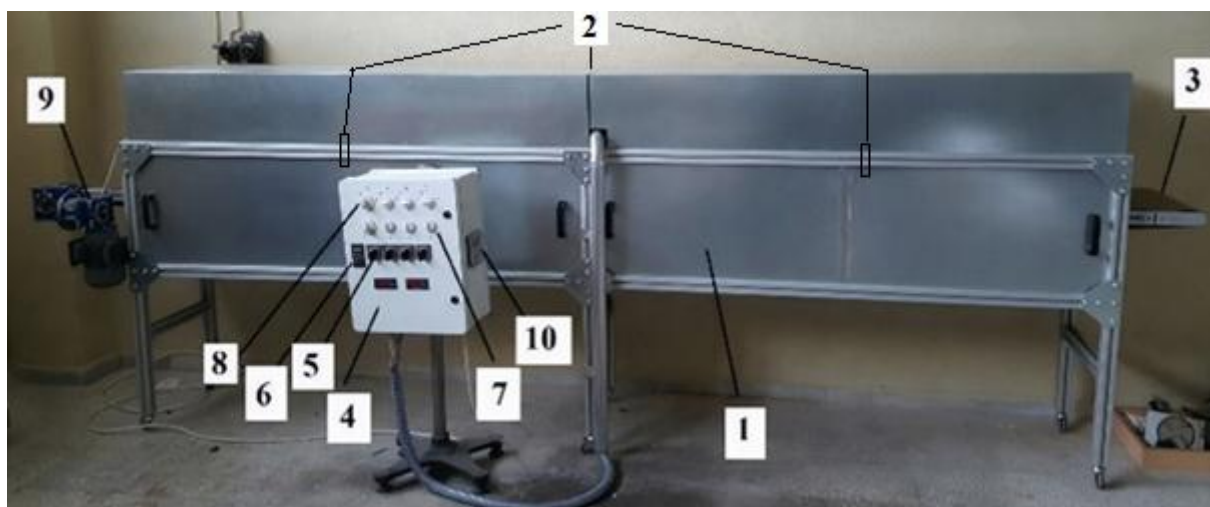

Figure 2. The experimental setup (1) Drying room (2) Magnetrons (3) Conveyor belt (4) Control box (5) Main switch (6) Conveyor speed control (7) Insurance (8) Microwave energy control (9) Electrical motor (10) Energy consumption meter

We measured the weight loss of the product with scale (Precica XB 620 M, Dietikon, Switzerland) of accuracy ± 0.001 g every five minutes. The initial moisture content of samples were determined at 105 ^{o}C for 24 hours. The drying process was finished when the moisture reached to 0.21 ± 0.5% (g water/g dry mater) from 7.62 ± 0.5% (g water/g dry mater) moisture.

2.3. Drying Analysis

Moisture content (MR) calculated from weight loss measured during drying is given in Eqn. (1) [21].

$$MR = \frac{M - M_e}{M_o - M_e} \tag{1}$$

where M (g water/g dry mater.min) is the moisture content at a specific time, M_o (g water/g dry mater. min) is the initial moisture content, M_e (g water/g dry mater. min) is the equilibrium moisture content. The M_e value is very small value compared to M and M_o. M_e can be simplified by taking zero as in Eqn. (2) [22, 23].

$$MR = \frac{M}{M_o} \tag{2}$$

Drying rate is the amount of moisture evaporating at a certain time [24]. The drying rate of carrot samples can be determined by Eqn. (3) [25]:

$$Drying\ rate = \frac{M_{t+dt} - M_t}{d_t} \tag{3}$$

where M_{t+dt} (g water/g dry mater) is the moisture content at $t+dt$, and dt is the time (min) interval between two consecutive measurements.

Microwave drying efficiency can be calculated by Eqn. (4) [26]:

$$\mu = \frac{m_w \lambda}{P.t} x100 \tag{4}$$

where μ is the microwave drying efficiency (%), P is the microwave output power (W) and λ is the latent heat of vaporisation of water.

2.4. Determination Of The Diffusion Coefficient And Activation Energy

D_{eff} varies depending on the properties of the product. It discloses all the mechanisms of moisture movement including fluid, vapor, surface diffusion, capillary and hydrostatic flow [27]. The change of the diffusion coefficient can be explained by an exponential function of the Arrhenius type. The second Fick law has analytical solutions for some simple geometries under specified conditions. In the calculations it is assumed that homogeneous internal distribution and infinite slabs geometry of carrot slices [28]. The slope method was used to calculate the effective moisture diffusion of the carrot slices. In general, the effective diffusion coefficient varies depending on the D_{eff}, the temperature and the physical properties of the product. In the literature, the relation between the effective diffusion coefficient (D_{eff}) and the temperature and the product properties is dealt by the Arrhenius equation. Several assumptions have been made in the solution of Eqn. (5-7), such as the constant initial moisture content, the symmetry of the mass transfer according to the center, the constant diffusion coefficient, neglecting the shrinkage [24].

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$$MR = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n-1)^2} \exp\left(-(2n-1)^2 \frac{\pi^2 D_{eff} t}{4L^2}\right) \tag{5}$$

$$\frac{M - M_e}{M_o - M_e} = \frac{8}{\pi^2} \exp\left(-\frac{\pi^2 D_{eff}}{4L^2} t\right) \tag{6}$$

$$\ln \frac{M - M_e}{M_o - M_e} = \ln \frac{8}{\pi^2} - \frac{\pi^2 D_{eff}}{4L^2} t \tag{7}$$

This equation is a linear connection.

$$Ln\ MR = a + ct \tag{8}$$

where D_{eff} is the effective diffusivity ($m^2\ s^{-1}$), L is the half of the sample thickness (m), t is the drying time (s), a and c is the coefficients. When a graph is drawn between $\ln \frac{M - M_e}{M_o - M_e}$ and t, the slope of the line is as in Eqn. (8). The diffusion coefficient from these slopes can be calculated from Eqn. (9).

$$Slope\,(Egim) = \frac{\pi^2 D_{eff}}{4L^2} \tag{9}$$

Since the temperature in the microwave dryer can not be determined exactly, the activation energy is calculated by changing the Arrhenius equation [8, 10]. The activation energy is described as the energy needed to start the drying process according to the material properties and the drying conditions. The slope method used to calculate the diffusion coefficient and the variation of the logarithmic value of the moisture ratio with respect to drying time were plotted for different powers and product weights [29].

$$D_{eff} = D_o . e^{-Ea.m/P} \tag{10}$$

where m is the mass of sample (g), P is the microwave power (W), D_0 is the pre-exponential factor ($m^2\ s^{-1}$). E_a ($W\ g^{-1}$) is the activation energy.

2.5. Electrical energy consumption

The electrical energy consumption during drying is recorded by the counter on the control panel. The energy consumed by the microwave conveyor drier can be calculated from Eqn. (11) [30]:

$$E = P.t \tag{11}$$

where E is the total energy consumed by the drier, (kWh)

3. Results and Discussion

At the end of microwave powered drying process, the amount of energy consumed for each parameter was determined in the range of 123.8 – 131.7 kWh as shown in Fig. 3. The energy consumption increased as result of eighter increase of applied microwave power or slice thickness. The lowest energy consumption was measured at slice thickness of 4 mm at 1050 W. This is because; less heat is produced at low microwave power and it lets more time passes for heat transfer

from the material to the environment. Thus, the amount of energy consumed to evaporate the water in the material is reduced.
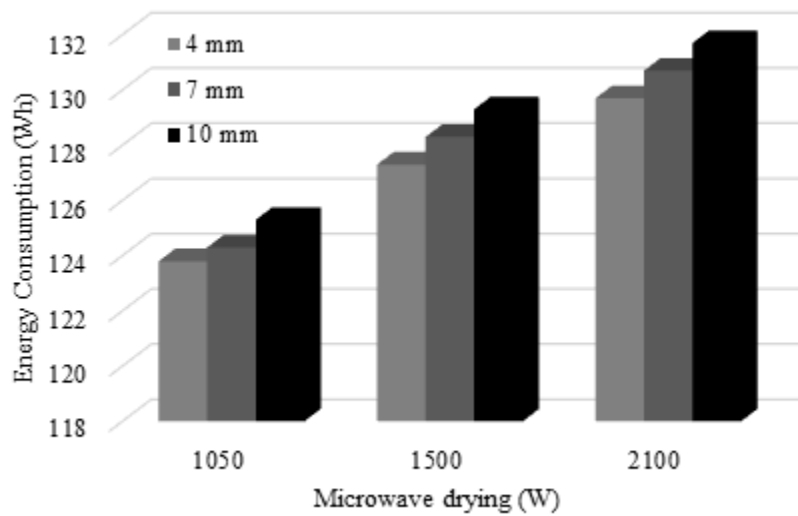

Figure 3. Energy consumption values during the drying of carrot

Ratio between drying efficiency at three select microwave powers are presented in Fig. 4 for microwave conveyor drying. For 4 mm slice thickness, for 1050, 1500 and 2100 W respectively 5.64, 9.8 and 12.96%, for 7 mm slice thickness 4.01, 5.15 and 9.33%, for 10 mm slice thickness 4.88, 7.23 and 10.58% of drying efficiencies were found. As the applied microwave power increased, drying efficiencies increased.
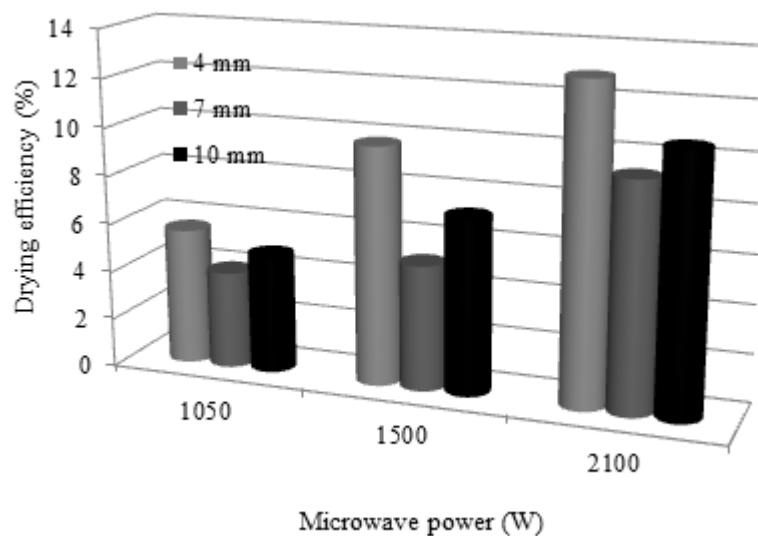

Figure 4. Drying efficiency at different powers

For the Equation 8 to be solved, Fig. 5-7, which is the changing of Ln (*MR*) according to time, must be drawn. The effective diffusion coefficients, ranging from 1.21×10^{-7} to 7.56×10^{-8} $m^2 s^{-1}$ increased by the increasing of the microwave power (as seen Table 1). Doymaz (2015) [5] has calculated the effective diffusion coefficients of carrot dried by infrared between 2.45×10^{-9} and 7.38×10^{-9} $m^2 s^{-1}$, and Haq et al. (2017) [31] has calculated between 6.78×10^{-11} and 6.03×10^{-10}. In other studies, it was also emphasized that effective diffusion coeffiency increases as the microwave power increases [32, 33]. General range of effective moisture diffusivity for different foodstuffs is between 10^{-9} and 10^{-11} [34]. In literature, diffusion coeffiency of carrot dried by different drier types are noted as follows: under natural sun between 1.97×10^{-10} and 2.15×10^{-10} $m^2 s^{-1}$ [35], infrared drying between

7.295×10^{-11} and 1.140×10^{-10} m^2 s^{-1} [36], natural convection solar drying between 3.15×10^{-7} and 6.36×10^{-8} m^2 s^{-1} [20].

Table 1. D_{eff} values for carrot that were dried using different microwave power levels

| Thickness	Microwave Power	Equation	a	c	D_{eff} (m^2 s^{-1})	R^2
4 mm	1050 W	ln(MR) = -0.0367t+0.0102	0.0102	-0.0367	5.94×10^{-8}	0.9908
	1500 W	ln(MR) = -0.0438t+0.1772	0.1772	-0.0438	7.09×10^{-8}	0.9939
	2100 W	ln(MR) = -0.0467t+0.0617	0.0617	-0.0467	7.56×10^{-8}	0.9930
7 mm	1050 W	ln(MR) = -0.0243t+0.0873	0.0873	-0.0243	1.21×10^{-7}	0.9975
	1500 W	ln(MR) = -0.0355t+0.2865	0.2865	-0.0355	1.76×10^{-7}	0.8301
	2100 W	ln(MR) = -0.0414t+0.0642	0.0642	-0.0414	2.05×10^{-7}	0.9951
10 mm	1050 W	ln(MR) = -0.0224t+0.1283	0.1283	-0.0224	2.27×10^{-7}	0.9937
	1500 W	ln(MR) = -0.0323t+0.0763	0.0763	-0.0323	3.27×10^{-7}	0.9925
	2100 W	ln(MR) = -0.0403t+0.0730	0.073	-0.0403	4.08×10^{-7}	0.9922
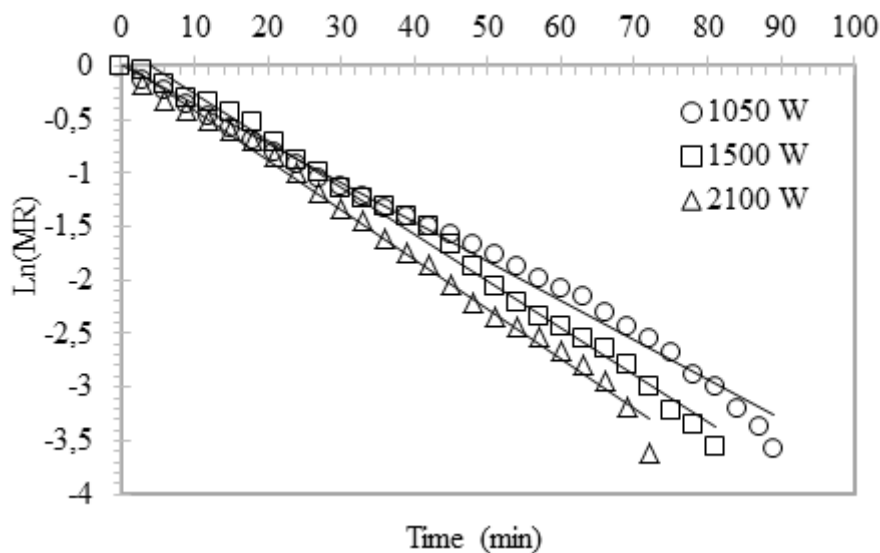
Figure 5. Estimation of moisture diffusivity coefficient of carrot with 4 mm layer thickness
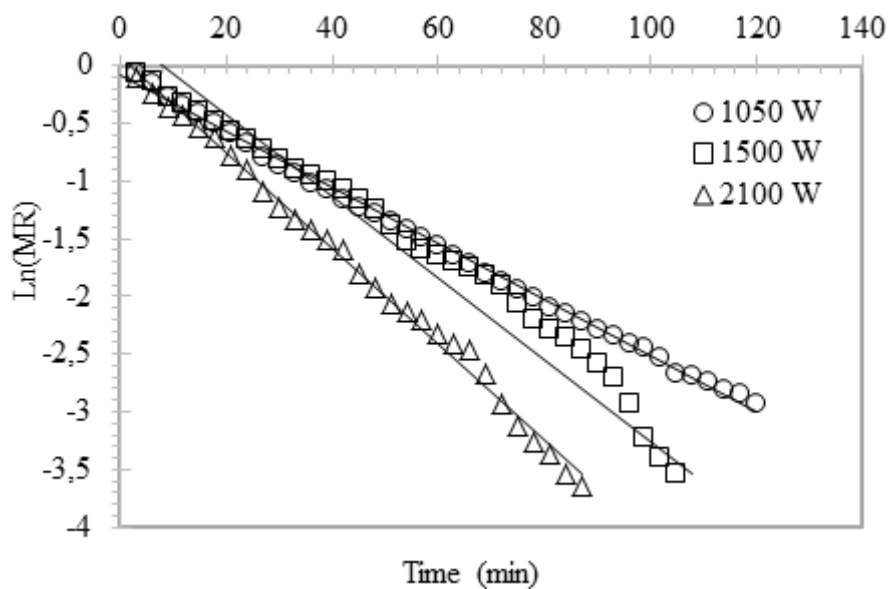

Figure 6. Estimation of moisture diffusivity coefficient of carrot with 7 mm layer thickness

Activation energy was acquired by drawing the graph of the *m/P* change of the natural logarithm of D_{eff} as shown in Fig. 8. Then, the dependence of the effective diffusivity of carrot samples on the microwave power can be represented by the equations in Fig. 8. It could be seen that, the activation energies for different slices of 4, 7 and 10 mm were respectively 118.52, 129.9 and 135.21 W g^{-1}, as shown in Fig. 8. Apparently, the activation energy increased with increasing slice thickness. It indicates that more energy was required to activate the drying of the sliced carrot samples considered in this study.
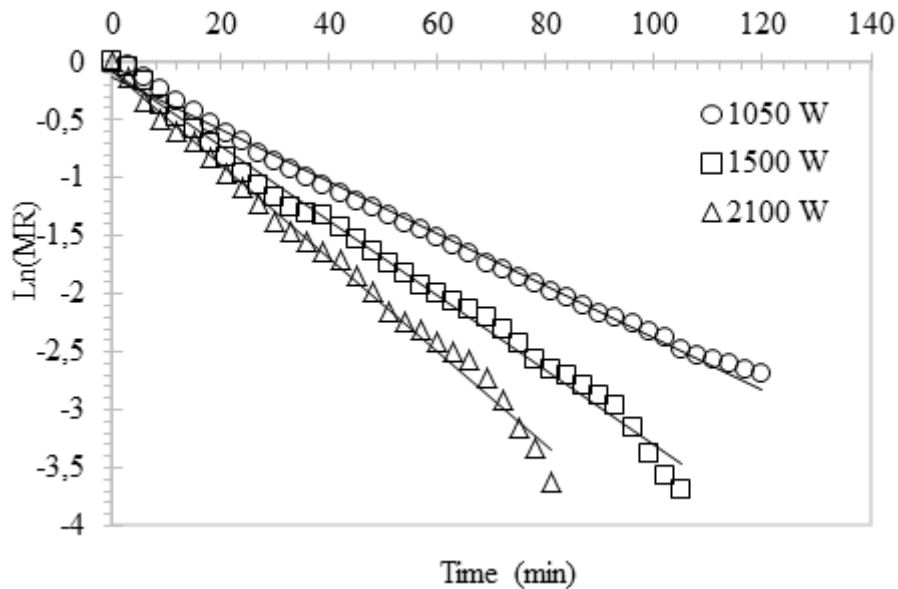
Figure 7. Estimation of moisture diffusivity coefficient of carrot with 10 mm layer thickness

The values we calculated are higher than that corresponding to carrot 4.247 kW kg^{-1} [5], pepper 14.19 W g^{-1} [28], mint leaves 12.283 W g^{-1} [37], apple 12.15 W g^{-1} [8] and potato 14.945 W g^{-1} [26].
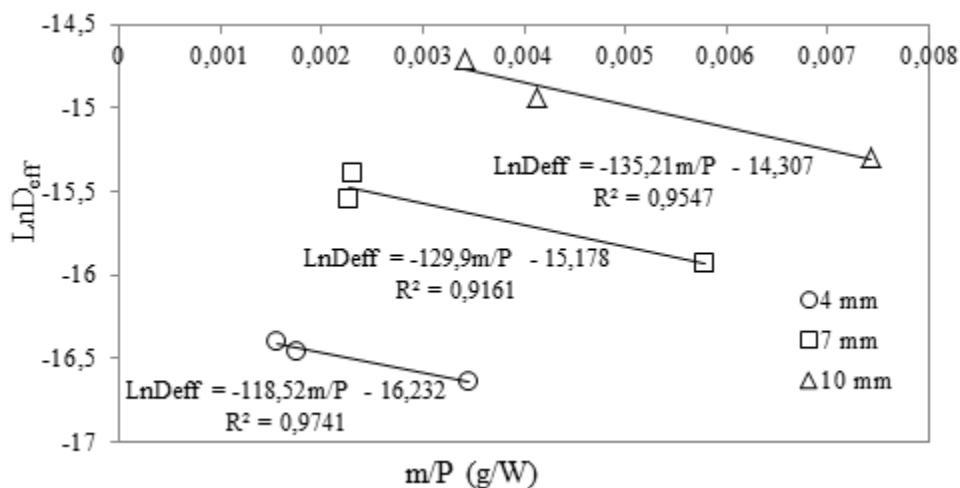
Figure 8. Relationship between D_{eff} and (*m/P*) for carrot slices.

Fig. 9 illustrates the influence of applied microwave power on drying rates. Drying rates were determined from the amount of water acquired per unit time. Moisture content of the carrot was too high in the initial stage of the drying process, leading to higher microwave energy absorption and higher drying rates due to high moisture distribution. As drying progressed, drying rate decreased due to diminishing moisture. Drying rates ranging from 1050 W to 2100 W microwave power were set between 0.004 and 0.32 g. As the microwave output power was increased, the drying rate of

sample has apparently increased [37]. This demonstrates the importance of the effect of applied microwave energy on drying rate. In the study of Wang and Xi (2005) [38] made by carrot and in our study, there has been an obvious bending point in drying rate curves.
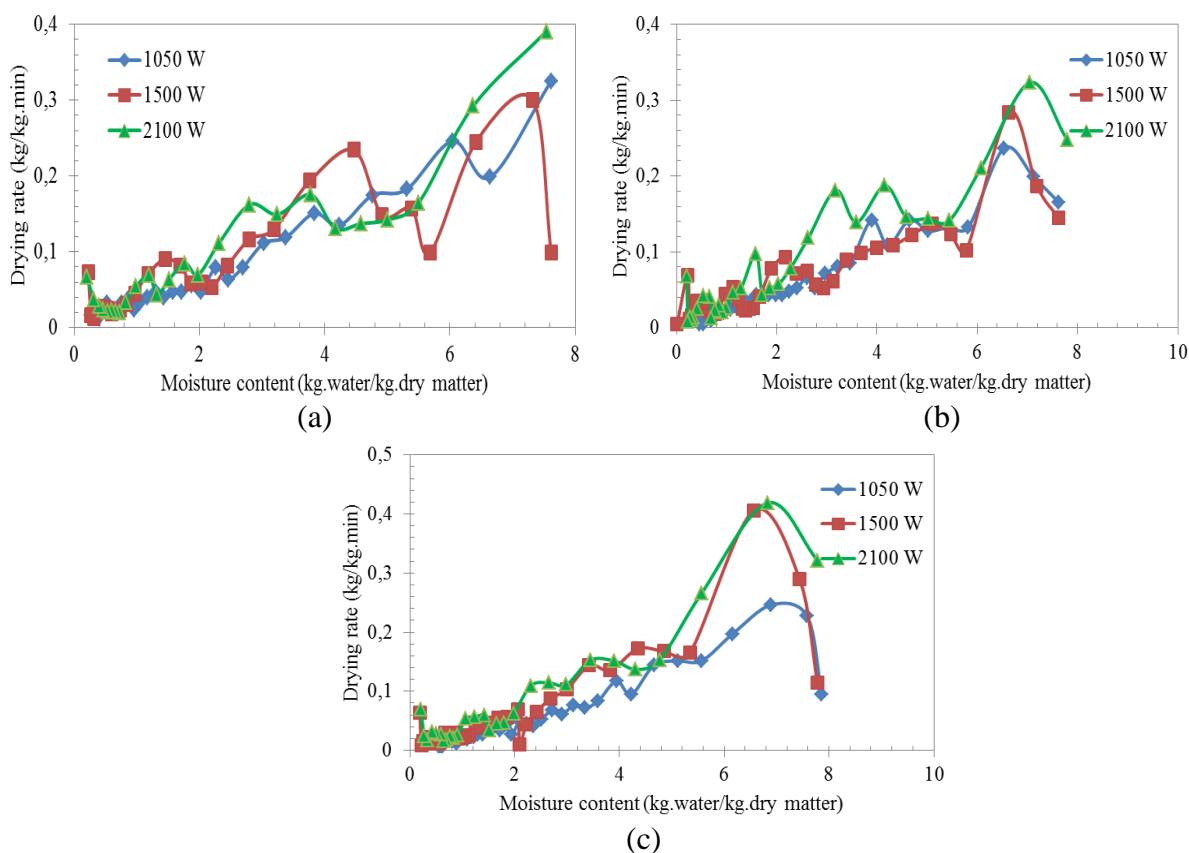

Figure 9. Variations of drying rate at different microwave power levels a) 4mm, b) 7mm, c) 10mm

Moisture content of the carrot was too high in the initial stage of the drying process, leading to higher microwave energy absorption and higher drying rates due to high moisture distribution. As the drying progresses, the rate of drying has decreased due to the decreasing humidity. High drying rates were achieved at high microwave power. This demonstrates the importance of the effect of applied microwave energy on drying rate. Similar findings are in accordance with the findings reported by Sarimeseli (2011) [33] and Maskan (2000) [14].

4. Conclusion

The effect of microwave conveyor drying on drying time, moisture content, energy consumption, drying rate, drying efficiency, activation energy and effective moisture diffusivity of carrot slices were investigated.

The concluding observations are as follows:

- Drying time increased with decreasing of microwave power level and this caused to decrease in consumed energy amount. Considering the results, the values obtained for total energy required for thin layer drying of carrot were in ranges of 123.8 – 131.7 kWh. The minimum energy consumption values were measured as 123.8 kWh for 1050 W power level, 0.245 m min^{-1} belt speed and 4 mm layer thickness.

- Drying rate increased rapidly at initial stage of microwave drying due to high rate of absorption of microwave energy by carrot. After the loss of moisture from carrot, the absorption of microwave energy decreased resulting in a decrease in drying rate. Drying rate increased with increasing of microwave power.
- Effective moisture diffusion depends on moisture content, it increases with decreases in moisture content and with increases in microwave power. Effective diffusivity values for carrot in microwave drying ranged from 1.21×10^{-7} to 7.56×10^{-8} m^2 s^{-1} for different carrot thicknesses and 118.52, 129.9 and 135.21 W g^{-1} for activation energy. We reached the conclusion that 1050W is the optimal microwave power in terms of drying duration and energy consumption in the process of microwave drying of carrots.
- This system, which provides low energy consumption and short drying time, is considered to be beneficial in all industrial areas (heating, drying, chemical, etc.). In this study, it proved that the problem of drying time and energy consumption is solved by microwave conveyor system.
- The results of drying made at low forces are good. However, the drying results at high power levels did not improve well. The product burned.
- Compared with the traditional drying methods, microwave drying can significantly shorten the drying time.

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