J. Agr. Sci. Tech. (2019) Vol. 21(5): 1131-1143

Design of Semisphere Solar-Microwave Hybrid Dryer and Drying Performance of Zucchini

S. Celen[1*], and S. Oguz Arda[1]

ABSTRACT

In this work, performance of a newly designed hybrid dryer was investigated. Drying was done with the support of solar energy to microwave conveyor dryer. By using collector, which was designed with semisphere shape for having high efficiency from solar energy, hot air was produced and moved through the tunnel with velocity of 3 m s^{-1} and by using 0.7, 1 and 1.4 kW microwave support, drying behavior of 5, 10, and 15 mm zucchini slices were examined. At the end of drying process, drying time, color changes of dried products, energy consumption, collector efficiency, and modelling of drying were determined. Considering the time required for drying the zucchini slices until reaching 10±1% (wb) moisture content and electrical energy consumption values, the most suitable results were obtained from 1 kW microwave power, air velocity of 0.245 m min^{-1}, and 5 mm zucchini slice thickness, corresponding to total energy of 1.143 kWh. The collector efficiency was calculated as 24.3%, under the environmental conditions of our study.

Keywords: Drying kinetics, Energy consumption, Mathematical modeling, Zucchini.

[DOR: 20.1001.1.16807073.2019.21.5.21.8]

INTRODUCTION

Drying of foods has been applied since old times with the aim of decrease in energy and increase in quality, and it has adapted itself to technological advances through this process (Rabha *et al.*, 2017). Drying for food processing gives possibility of designing new product formulations and increasing shelf life of foods and vegetables (Mohammadi *et al.*, 2014). Before starting the drying of foods and vegetables in small or big scale, choice should be made properly depending on purpose. It is not possible to say only one drying method is economical for all foods and suitable for the end product quality. Therefore, for different products different drying methods should be applied with optimum drying parameters with the aim of having desired quality parameters and economical production. Nowadays, there exists lots of drying methods and they can be used either alone to dry a product or in a combination which gives positive effects on the end product quality and economy of drying (Puligundla *et al.*, 2013). For modern drying appliances that were designed well in industrial scale, energy was used more effectively, and obtaining a higher quality end product is possible (Bingöl and Devres, 2010).

Increasing energy costs, consumers' increasing anticipation on quality criterias, and increasing greenhouse gases causing climate changes throughout the worldwide demonstrate that research and development facilities are going to continue in the near future in effective ways. Thanks to better designed and made smaller dryers, drying machines using energy intensively can be performed with savings on the operation cost (Bingöl and Devres, 2010).

Many factors restrict the use of microwave energy alone in the drying. Although microwave energy begins to heat moist parts of the food easily, sometimes, there can be situations with nonhomogeneous heating profiles because of non-uniform energy

---

[1] Department of Mechanical Engineering, Namık Kemal University, 59860, Tekirdağ/Turkey.
*Corresponding author; e-mail: scelen@nku.edu.tr

inside the microwave oven. To overcome this problem, waveguides and rotary mixers can be added to the microwave ovens. Moreover, in the last stages of drying, because of small amounts of moisture content in the product, temperature can be increased rapidly. Many methods are developed for overcoming the restrictions of lone usage of the microwave energy in the drying. One of them is combining microwave drying with other methods (Zang *et al.*, 2006). Combined use of the microwave energy with other methods increases homogeneous distribution of the temperature inside the product, provides more control on the moisture content transfer, and increases drying velocity (Datta *et al.*, 2005). Method of drying with microwave was started to be applied with the combination of the methods of hot air, vacuum, freeze drying, and osmotic dehydration (Karaaslan and Tunçer, 2009; Ekow *et al.*, 2013). Food drying by using solar energy is a cheap method used in different climates and it has been studied by many researchers (Jairaj *et al.*, 2009; Tosun *et al.*, 2009; Aktaş *et al.*, 2012).

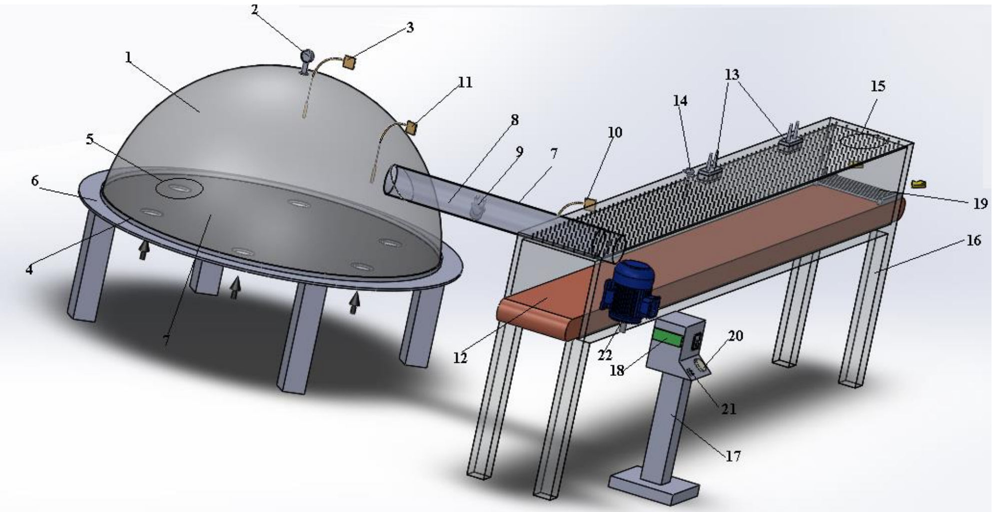
Because of exposing the product to high temperatures, drying methods with hot air take a lot of time and cause undesired changes to the dried product's physical, chemical, and sensory features (Soysal *et al.*, 2009). One of the problems associated with thermal drying methods is shrinkage and hard-shell formation. To prevent these negative effects on the product and with the purpose of obtaining more quality products, microwave hot air drying method was developed as a result of recent researches. To produce microwave heat, polar water molecules are affected directly. Heat is formed inside the product directly. Moisture that is inside the product is heated and evaporated in very short time periods and, because of the steam pressure difference between internal and external environment, moisture transfer occurs from inside to outside. Thanks to this, heat transfer problem occurring at the traditional drying methods are exceeded (Soysal *et al.*, 2009). Moreover, the implementation of the combination of hot air and microwave shortens drying time significantly. Hot air and microwave are used for many food processing implementations instead of traditional drying with hot air method with the aim of shortening drying time and increasing product quality (Karaaslan and Tunçer, 2009; Workneh and Oke, 2012).

Drying method used in this work sent circulated and heated air inside the closed environment over the product. This method provides more controlled drying than open drying. The purpose of using the moving system is to allow the product to dry homogeneously. If the product moves along the belt, microwave beams are then able to contact the entire surface of the product. This design is based on drying air passing through semi-spherical solar collector, and heating the air by free solar energy source that is transmitted through the product via forced convection and microwave energy. This system was designed for low temperature drying. Zucchini was selected as biological material for trying the performance of this system and changes in color quality. The aim of drying biological material was to obtain good quality dried product with low energy consumption in a short time, and using renewable energy.

MATERIALS AND METHODS

Zucchini (*Cucurbita pepo L.*) used in this study was grown in Turkey and was obtained from Tekirdağ City's local supermarket and was kept at +4ºC in the refrigerator until being dried .

The combined microwave belt and solar energy dryer consisted of drying tunnel, two microwave power unit, teflon band, electrical engine, measurement probes and control cabinet, as shown in Figure 1. Dimensions of drying tunnel are 0.5×0.4×3.5 m. While every microwave power unit is 700W (2,450 Hz frequency), it can be arranged by control cabinet. The solar collector used for



1. Collector room; 2. Pyranometer; 3. Termocupl; 4. Thermometer; 5. Isolation; 6. Platform; 7. Collector; 8. Channel; 9. Fan; 10. Anemometer; 11. Thermometer; 12. Belt; 13. Magnetron; 14. PT; 100 Thermometer; 15. Drying room; 16. Stand; 17. Control panel; 18. Energy meter; 19. Tray; 20. Power; (on/off) 21. Potentiometer, 22. Electric motor.

Figure 1. A Schematic Picture of Experimental System.

producing hot air was made from acrylic material, enabling light intensity permeability with 1.5 m diameter half-spherical form with the aim of taking advantage of incidence angle of solar rays. Galvanized cylindrical channel linking collector to drying tunnel, with 1 m length and 0.13 m diameter, is wrapped with the insulation material for preventing heat loss and is used with the aim of producing heat to be transported by a fan (35 W, HCM-180 N, Turkey). Temperature measurements were made by putting thermocouples in the center and exit of the collector (Proskit Nt-312, ±1°C, Taiwan), exit of the cylindrical channel and inside the tunnel (CEM DT 318, ±0.8%, India). Moreover, the potentiometer was also used for the flow rate adjustment of the hot air and for measuring the speed anemometer (CEM DT 318, ±3%, India) was linked to the pipe exit. To weigh the zucchini slices, Precisa XB 620M model (Precisa Instruments AG, Dietikon, Switzerland) electronic scales with 0.001 g precision were used during the experiments, during which the instant sunlight intensity was measured with CEM brand DT-185 Model device (Shenzhen Everbest Machinery Industry Co. Ltd., made in India).

Experimental Procedure

For drying operations, quality of the product depends on parameters such as velocity, temperature, and proper relative moisture of the drying air. If they are not arranged properly, products can be dried with more time and poor quality. In similar manner, high relative moisture and low air velocity cause longer drying time and, depending on this, more energy consumption (Aktaş *et al*., 2012). The aforementioned variables are specified to perform zucchini drying operation properly using a combined microwave conveyor and solar energy dryer with a less energy consumption, no other cost except for initial investment cost which was designed and manufactured.

Prior to the drying experiment, the zucchinis were cut into slices with thickness of 5, 10, and 15 mm. There was no other pre-treatment applied, except for washing. Before starting the drying experiments, for calculating first values of moisture content of zucchini slices, their dry weights were determined after 24 hours at 103± 2°C in oven. As a result of this, the first values of moisture content were determined as 85±0.7% (wb) (Arda, 2016).

Experiments were carried out at 0.7, 1, and 1.4 kW microwave powers. Throughout the work, conveyor belt speed was kept at 0.245 m min^{-1}. Air inside the collector was kept until reaching constant temperature and the air was transferred to the tunnel with velocity of 3 m s^{-1}. Every five minutes, the product weight was measured by using precision scales to calculate moisture loss. These processes were continued until zucchinis' moisture content reached 10±0.7% (wb). Trials were repeated three times and averages of the data were used.

Mathematical Modelling

Different types of products and systems should be examined with different models being formed with heat, mass, momentum transfer and material science. Modeling the drying behavior effectively is important for investigation of drying characteristics of the samples. In this work, with the help of non-linear regression analysis, moisture rate-time change curves were modelled using experimental results of different microwave power values. Moisture rate is defined as in Equation (1) (Mazandarani *et al.*, 2017).

$$MR = \frac{m - m_e}{m_o - m_e} \qquad (1)$$

Where, the values of m_e (equilibrium dry basis moisture contents) are relatively small compared to m (wet basis moisture content at any time 't') and m_o (initial moisture content), and error implied in the simplification is negligible (Dinani *et al.*, 2014; Simha *et al.*, 2016). Therefore, the equilibrium moisture content was assumed zero for microwave drying. Drying curves were obtained for the zucchini samples. The experimental moisture ratio versus drying time data were fitted in seven thin-layer drying models in Table 1.

Coefficients for these model are determined by applying non-regression analysis in the XLSTAT data analysis software. While "a_o, a, a_1, a_2, b, n, k, k_1, k_2, g" are model coefficients, "t" is the time.

To determine the most suitable model, some statistical parameters should be calculated. These are R^2, e_s and χ^2 values. The coefficient of determination (r^2) is one of the criteria used for specifying curve suitability. In addition to the coefficient of determination usually, standard error of estimate (e$_s$) and *Chi* square (χ^2) are the other parameters used for determining regression suitability (Kutlu *et al.*, 2015). To get the best fit of the experimental data, the coefficient of determination should be higher and the χ^2 and e_s should be lower. These parameters are defined through Equations (2-4) (Çelen *et al.*, 2010).

$$r = \frac{n_o \sum_{i=1}^{n_o} MR_{teo,i} MR_{\exp i} - \sum_{i=1}^{n_o} MR_{teo,i} \sum_{i=1}^{n_o} MR_{\exp,i}}{\sqrt{n_o \sum_{i=1}^{n_o} (MR_{teo,i})^2 - \left(\sum_{i=1}^{n_o} MR_{teo,i}\right)^2} \sqrt{n_o \sum_{i=1}^{n_o} (MR_{\exp i})^2 - \left(\sum_{i=1}^{n_o} MR_{\exp,i}\right)^2}} \qquad (2)$$

$$e_s = \sqrt{\frac{\sum_{i=1}^{n_o} (mr_{teo,i} - mr_{\exp,i})^2}{n_o}} \qquad (3)$$

Table 1. Empirical and semi-empirical models which are used often to express the drying behavior of biological materials ^{a}.

Models	Model equation	Models	Model equation
Newton	$MR = \exp(-kt)$	Two term	$MR = a_1 \exp(-k_1 t) + a_2 \exp(-k_2 t)$
Logarithmic	$MR = a_0 + a \exp(-kt)$	Verma *et al.*	$MR = a \exp(-kt) + (1-a) \exp(-gt)$
Logistic	$MR = a_0 /(1 + a \exp(kt))$	Wang and Singh	$MR = 1 + at + bt^2$
Midilli *et al.*	$MR = a \exp(-kt^n) + bt$		

^{a} (Kahveci and Cihan, 2008; Zomorodian and Moradi, 2010). Red highlighted items in table 1 are missing in references.

$$\chi^2 = \frac{\sum_{i=1}^{n_o} (mr_{teo,i} - mr_{\exp,i})^2}{n_o - n_c} \quad (4)$$

Where, $mr_{pre,i}$ is the ith predicted moisture ratio, $mr_{exp,i}$ is the ith experimental moisture ratio, n_o is the number of observations, and n_c is the number of coefficients in the drying model.

Color Change

Upon drying the zucchini slices, to determine the effects of drying conditions on the products, color measurements were made on fresh and dried product samples. Color of a dried product can be measured by a colorimeter (Spec brand HP-200 model) in CIE (Commission Internationable d'Eclairage) Lab chromaticity coordinates (Bala and Hossain, 2012; Ulloa *et al.,* 2008). Color measurements were made depending on international $L^*a^*b^*$ system with Hunter Lab D25LT (USA) appliance. L^* value states brightness and can have values between 0 and 100. Positive a^* values represent redness, negative a^* values represent green color. Positive b^* values represent yellowness, negative b^* values represent blue color. For dull colors, chroma values are low, while for vivid colors chroma values are high. Color change can be calculated through Equations (5-8) (Polatcı and Tarhan, 2009; Soleimanifard *et al.,* 2018; Safary and Chayjan, 2016).

$$\Delta L = L_{fresh} - L^* \quad (5)$$

$$\Delta a = a_{fresh} - a^* \quad (6)$$

$$\Delta b = b_{fresh} - b^* \quad (7)$$

$$\Delta E = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2} \quad (8)$$

Energy Consumption

Energy consumption was measured with an electric counter (Köhler AEL.MF.03, Turkey). Energy consumption values of microwave conveyor dryer, magnetrons and fan were recorded using this device. For every parameter, energy consumption values as a result of the experiments were recorded.

Solar Energy

The solar constant, which is perpendicular to the unit area, was measured as 1,007 W m^{-2} on average for Tekirdağ in the days 230-232 of the year.

The available solar energy inside the solar dryer (Q) could be calculated in terms of the solar radiation that penetrated the cover and the net surface area of the dryer in Eq. 9:

$$Q = I.A_k \quad (9)$$

Air solar-collectors instantaneous thermal efficiency is calculated in Equation (10) (Bulut and Durmaz, 2006).

$$\mu = \frac{\dot{m}C_p(T_{out} - T_{in})}{IA_k} \quad (10)$$

Where, $\dot{m}$ is the mass flow of the air (kg s^{-1}), C_p is the specific heat of the air (1,005 J kg^{-1} °C), T_{out} is the outlet Temperature of the air from the collector, T_{in} is the inlet Temperature of the air from the collector, I is the total solar radiation coming to the collectors surface (W m^{-2}), and A_k is the collectors surface Area. The rate of the mass flow is calculated by Equation 11;

$$\dot{m} = \rho V A_ç \quad (11)$$

Where, ρ (kg m^{-3}) is the density of the moist air and it is taken from the table showing its average inlet and outlet temperature and relative moisture. V (m s^{-1}) shows the speed of the air flow, and $A_ç$ (m^2) shows the collector outlet's cross-sectional Area.

RESULTS AND DISCUSSION

Drying Behaviors

In this work, zucchini's drying behaviors were examined with three different microwave power levels (0.7, 0.1, and 1.4 kW), different slices (5, 10 and 15 mm) and different collector temperatures. As a result of these trials, when slice thicknesses increased, drying time increased. Collector exit temperature and collector center temperature changes depending on environmental temperature. Depending on this, drying temperature also changes and affects drying time. Inside the tunnel, temperature changes depending on both hot air coming from the tunnel and effects of solar rays (Figure 2). That is why it does not have a constant value. Drying time of 0.7 kW power lasted between 60-85 minutes, 1 kW power's drying time lasted between 47-78 minutes, and 1.4 kW power's drying time lasted between 67-95 minutes. For 1 kW power, drying time was lower than the others. The reason for this was that air temperature that was transferred to the drying atmosphere had higher temperature, as shown in Figure 2. In some times of the day, because of the changing environmental temperature, drying temperature also changed.

As it is seen in Figure 3, for the first phase of the drying, microwave energy transforms to the thermal energy for food with higher relative moisture content, and the product's temperature begins to rise with time. Liquid inside the solid material is quickly heated until boiling point. When vapor pressure of product's moisture is higher than the environment's vapor pressure, product begins to lose moisture. The second phase is rapid drying phase. Thermal energy that is gained thanks to the microwave energy is used to provide evaporation energy. When the boiling point of the liquid inside the solid is not reached, it can be observed that temperature rises throughout the drying process. The third phase is the decreasing drying phase. Since the energy required for evaporation is lower than thermal energy which is gained from microwave energy, temperature of the moisture inside the product can be higher than boiling temperature (Metaxas and Meredith, 1983).

As Boldor *et al*. (2005) stated, when liquid evaporated because of the pressure difference, this constant drying period was the second phase. In the third phase, because of having less water, material's temperature can rise rapidly and burning can occur. In contrast to the drying with hot air in which the product's final temperature is never higher than air temperature, it is harder to control product's final temperature for microwave drying (Zhang *et al*., 2006).

There exist lots of dryers in the dryer technologies. As a result of investigations made, tomato drying lasted 6-8.5 hours for solar energy drier (Aktaş *et al*., 2012), carrot slices drying lasted 7.25-7.5 hours for freeze drying, microwave energy drying and the combination of hot air. Carrot slices drying lasted 9.5 hours for only freeze drying (Litvin *et al*., 1998), zucchini was dried with convection nearly for 12-50 hours. In Dimitrios *et al*. (2014) study, red pepper was dried with the combination of the hot air (50–75°C) and lyophilization (0.05, 7 and 13 kPa) for

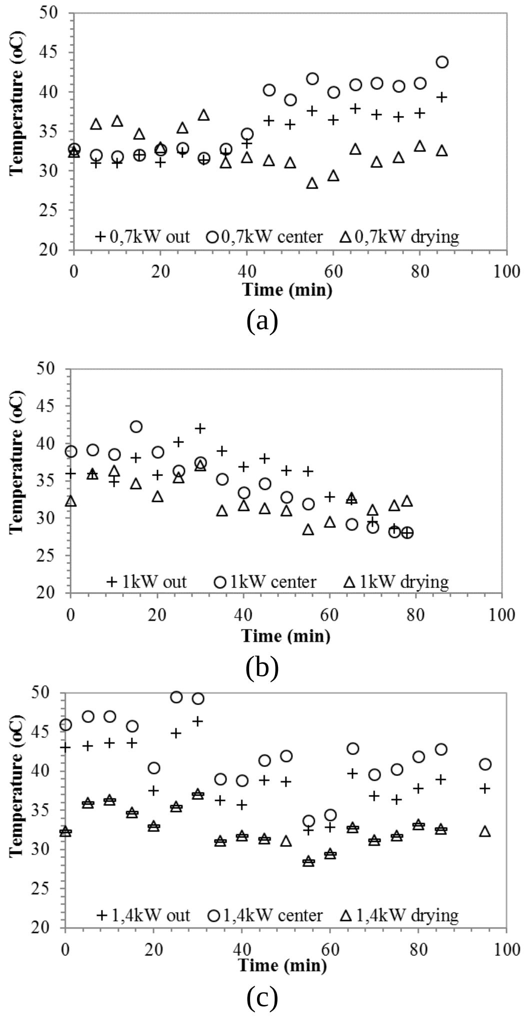
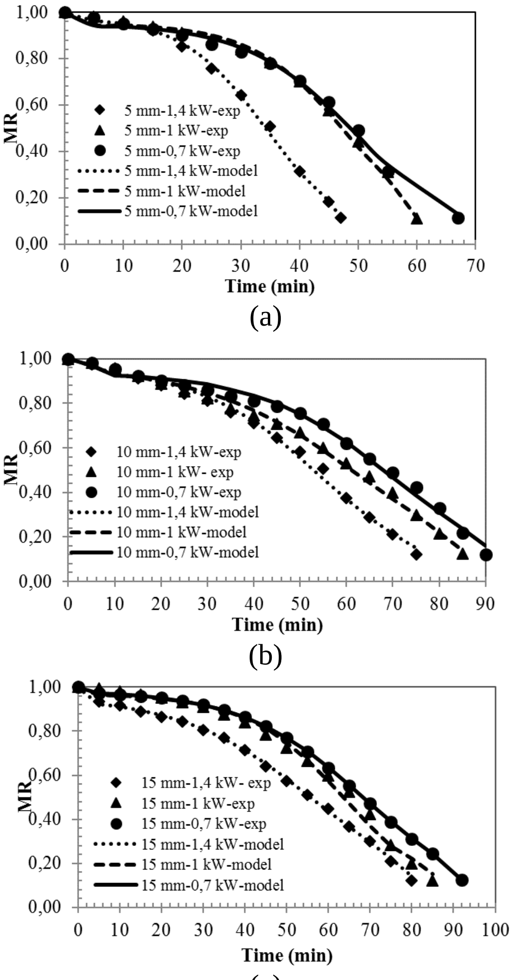


Figure 2. Central point of the solar collector, solar collector exit and drying entrance to the tunnel's temperature changes with time: (a) 0.7; (b) 1, (c) 1.4 kW.



(a)

(b)

(c)

Figure 3. Drying curves for 5 mm zucchini slices (a) 10 mm zucchini slices (b) 15 mm zucchini slices (c) based on the Logistic Model.

3– 9.17 hours. Alibas (2012) conducted squash drying during 1.5-8 hours at 40–80ºC. Also, Ertekin and Yaldız (2010) conducted apple slices drying for 5-25 minutes at microwave energy of 200-600W (Zarein *et al.*, 2015). It is demonstrated that our design dries the materials in shorter time than other drying methods. It lasted longer time than only microwave energy, but for product quality, our design is more advantageous.

Results of the Color Parameters

Before beginning the drying operation for the aim of determining color changes, 3 repeated color measurements were made for every experimental condition before and after drying. Color parameters of the dried products were compared with color parameters of the fresh products and color losses were determined. As a result of the drying, the value changes of the brightness (*L*) for 0.7 kW power and for 5, 10, and 15 mm slice thicknesses were found as 6.87, 6.84, and 18.0, respectively. For 1 kW power and 5, 10, and 15 mm slice thicknesses the values were 11.29, 9.50, and 17.73, respectively, and for 1.4 kW power the corresponding values were 3.58, 11.31, and 35.2, respectively. The total color change parameter for 0.7 kW power and 5, 10, and 15 mm slice thicknesses were found as 14.89, 9.73, and 20.60, respectively. The corresponding values for 1 kW power were found as 17.04, 16.23 and 20.81, and for 1.4 kW power, they were 11.65, 17.13, and 38.41, respectively. As a result of the drying, ΔL and ΔE for 0.7 kW power and 10 mm slice thickness was the best compared to other treatments. Impact of the drying on color changes of the zucchini slices is shown in Figure 4. Microwave drying of vegetables and fruits has attracted considerable attention because of high mass transfer coefficients and usually obtaining better dried product (Bingöl and Devres, 2010).

Energy Consumption

Appliances causing energy consumption are teflon band's electrical engine, magnetrons, and fan, which is at the solar collector. Throughout the drying, total energy consumption of the experimental setup was measured for 0.7 kW power as 1.210, 1.519, and 1.723 kWh, for 1 kW power as 1.143, 1.807, and 1.813 kWh, and for 1.4 kW power as 1.621, 2.025 and 2.512 kWh, respectively. When microwave power increased, the consumed energy also increased. When slice thicknesses were also compared, the consumed energy also increased. However, for 1 kW power drying experiment, energy consumption values were less when compared to the others. Since temperature of solar heated air was higher, drying time was

[DOR: 20.1001.1.16807073.2019.21.5.21.8]

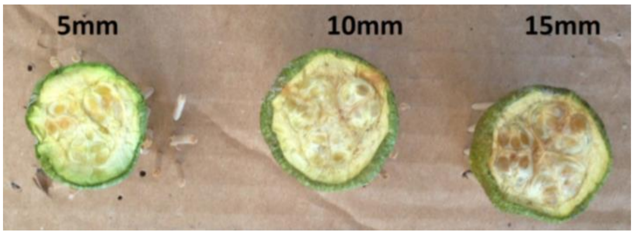


Figure 4. Photograph of the dried zucchini slices.

shorter. Consequently, consumed energy was less.

Instead of using microwave energy alone, using combined microwave belt and solar energy dryer led to significant time and energy savings during works. Wang and Sastry (2000) heated cylindrical carrots, potatoes, and sweet potatoes to 50 and 80°C by using microwave, and then they reported drying time was reduced with hot air. For continuous dryer with solar energy, solar collector provided heat energy at 0.2 m s^{-1} air velocity for 40°C as 1.908 kWh, for 45°C 2.043 kWh, and for 50°C, 2.237 kWh (Aktaş *et al*., 2012). In Table 2, specified energy consumption values are less compared to the other drying methods.

Modelling of the Drying Behaviors and Selection of Suitable Model

Modelling of drying operation in microscopic dimensions is about material's internal structure and usually independent of features of the equipment. Results of the coefficients of the drying models *ao*, *a*, and *k* are given in Table 3. Considering the whole slices with the values for r^2 (0.931-0.998), e_s (0.013-0.078), and χ^2 (0.0001-0.006), the most suitable model is Logistic Model in Table 4. In Figure 3, comparisons of the drying curves based on this model are shown.

Table 2. Energy consumption values at different microwave power and slice thickness.

Slice thickness, belt speed, microwave power	Drying time	Energy consumption
5 mm, 0.245 m min^{-1}, 0.7 kW	60 min	1.210 kWh
10 mm, 0.245 m min^{-1}, 0.7 kW,	82 min	1.519 kWh
15 mm, 0.245 m min^{-1}, 0.7 kW	85 min	1.723 kWh
5 mm, 0.245 m min^{-1}, 1 kW	47 min	1.143 kWh
10 mm, 0.245 m min^{-1}, 1 kW	68 min	1.807 kWh
15 mm, 0.245 m min^{-1}, 1 kW	78 min	1.813 kWh
5 mm, 0.245 m min^{-1}, 1.4 kW	67 min	1.621 kWh
10 mm, 0.245 m min^{-1}, 1.4 kW	85 min	2.025 kWh
15 mm, 0.245 m min^{-1}, 1.4 kW	95 min	2.512 kWh

[DOR: 20.1001.1.16807073.2019.21.5.21.8]

During drying of the material with homogeneous and porous structure, physical changes and chemical reactions occur and these are affecting the moisture transfer mechanism inside the product. When it is considered that food items' structure is nonhomogeneous, troubles through modelling become more understandable. Heat and mass transfer can be effective on each other and material's physical and chemical properties, then, as a cycle, they show interaction (Mujumdar and Zhonghua, 2008). Combined use of the microwave energy with different drying methods increase the homogeneity of the temperature distribution inside the product, provide more control over the moisture transfer, and

Table 3. Coefficients of the best model at different microwave power and slice thickness.

Slice thickness	Microwave power	Coefficients
5 mm	0.7 kW	ao= 0.952/ a= 0.002/ k= 0.126
	1 kW	ao= 0.983/ a = 0.008/ k= 0.139
	1.4 kW	ao= 0.953/ a = 0.005/ k= 0.107
10 mm	0.7 kW	ao= 0.966/ a = 0.022/ k= 0.062
	1 kW	ao= 0.941/ a = 0.00005/ k= 0.161
	1.4 kW	ao= 0.960/ a = 0.015/ k= 0.078
15 mm	0.7 kW	ao= 0.961/ a = 0.029/ k= 0.062
	1 kW	ao= 0.971/ a = 0.004/ k= 0.085
	1.4 kW	ao= 0.986/ a = 0.009/ k= 0.068

Table 4. Analysis results of the drying models for 5, 10 and 15 mm zucchini slices at different microwave power.

Slice thickness		5 mm			10 mm			15 mm		
Models	MP (kW)	r^2	e_s	$\chi2$	r^2	e_s	χ^2	r^2	e_s	χ^2
Wang and Singh	0.7	0.989	0.033	0.001	0.989	0.029	0.001	0.995	0.020	0.0004
	1	0.998	0.016	0.0002	0.873	0.090	0.008	0.983	0.034	0.001
	1.4	0.988	0.032	0.001	0.966	0.056	0.003	0.998	0.013	0.0001
Newton	0.7	0.811	0.163	0.027	0.826	0.179	0.032	0.837	0.147	0.022
	1	0.890	0.116	0.014	0.892	0.116	0.013	0.889	0.135	0.018
	1.4	0.909	0.111	0.012	0.915	0.108	0.012	0.862	0.146	0.021
Logarithmic	0.7	0.878	0.111	0.012	0.947	0.082	0.007	0.972	0.059	0.004
	1	0.948	0.103	0.011	0.742	0.133	0.018	0.877	0.112	0.013
	1.4	0.907	0.099	0.010	0.948	0.072	0.005	0.927	0.080	0.006
Logistic	0.7	0.990	0.032	0.001	0.978	0.042	0.002	0.998	0.012	0.0001
	1	0.997	0.020	0.0003	0.931	0.078	0.006	0.979	0.043	0.002
	1.4	0.995	0.023	0.001	0.987	0.036	0.001	0.998	0.013	0.0001
Midilli *et al.*	0.7	0.952	0.081	0.006	0.951	0.066	0.004	0.996	0.022	0.0004
	1	0.999	0.010	0.0001	0.938	0.080	0.006	0.967	0.067	0.005
	1.4	0.950	0.077	0.006	0.982	0.050	0.003	0.966	0.066	0.004
Two term	0.7	0.911	0.102	0.010	0.943	0.071	0.005	0.976	0.049	0.002
	1	0.958	0.085	0.007	0.780	0.128	0.016	0.999	0.007	0.00004
	1.4	0.928	0.088	0.008	0.949	0.076	0.006	0.950	0.071	0.005
Verma *et al.*	0.7	0.811	0.180	0.033	0.890	0.124	0.015	0.909	0.118	0.014
	1	0.847	0.147	0.022	0.689	0.162	0.026	0.817	0.162	0.026
	1.4	0.837	0.162	0.026	0.889	0.145	0.021	0.862	0.155	0.024

increase the drying velocity (Datta *et al.*, 2005).

Collector Efficiency

First of all, the solar constant in the Tekirdağ province where the experiment was conducted between the days 230th-232nd (in 2016) was measured as 1,007 W m^{-2} on average. In addition, the outside air temperature, relative humidity, and wind velocity was measured as 31°C, 63%, and 2 m s^{-1}, respectively. The instantaneous thermal efficiency of the solar collector was calculated to be 24.3%. The semi-spherical collector and other methods were compared. In a similar study, Metaxas and Meredith (1983) and Aktaş and Kara (2013) calculated the efficiency of the collector used as 53 and 56.7%, respectively. Compared to other solar systems, the drying system we designed can heat up more air and send it to the drying chamber. We calculated the collector efficiency as 24.3% under the environmental conditions of our study. The efficiency will increase if the drying system is better insulated and if drying is done in external weather conditions without any airflow.

CONCLUSIONS

In this work, microwave power levels were applied as 0.7, 1, and 1.4 kW, with three drying times of 60-85, 47-78, and 67-95 minutes. Considering the time required for drying the zucchini slices until reaching 10±1% (wb) moisture content and electrical energy consumption values, the most suitable results were obtained at 1 kW microwave power, air velocity of 0.245 m min^{-1}, and 5 mm zucchini slice thickness, corresponding to total energy of 1.143 kWh. Increasing microwave power for all slice thicknesses caused an increase in drying time and energy consumption values. Quick drying was obtained at 1 kW microwave power levels because of the high air temperature that was transferred to the drying tunnel. That is why low energy consumption values were obtained.

Regarding color criteria, the best results were obtained for 0.7 kW power drying operations compared to the other treatments, while taking into consideration (ΔL) and (ΔE) values. The best result was obtained at 0.7 kW microwave power level with 10 mm zucchini slice.

To predict moisture rate, “Logistic” drying model was chosen as the most predictive drying kinetics model, considering the comparisons made based on coefficients of the examined drying models. Logistic” drying model had the highest R^2 value based on microwave power and slice thicknesses, in all experimental conditions.

Compared to other solar systems, the drying system we designed can heat up more air and send it to the drying chamber. We calculated the collector efficiency as 24.3% under the environmental conditions of our study.

The solar microwave hybrid dryer yielded good results in terms of drying time, energy consumption, and product quality. It can be used in industrial field for drying sensitive products.

Nomenclatures

a, a_o, a_1, a_2, b, k, k_1, k_2, g, n : Drying constants

$A_ç$:	The collector outlet’s cross-sectional Area, [m^2]
A_k:	The collectors surface Area, [m^2]

a^*, b^*, L^*: Color parameters

C_p:	The passing air specific heat, [J kg^{-1} °C]
e_s:	The standard error
I:	The total solar radiation, [W m^{-2}]
I_{sc}:	Solar constant
L:	Half thickness of the black radish slices, [m]
m:	Moisture content, [g water g^{-1} dry matter]
m_o:	Initial moisture content, [g water g^{-1} dry matter]

[DOR: 20.1001.1.16807073.2019.21.5.21.8]

MR:	Dimensionless Moisture Ratio
$MR_{pre,\,i}$:	*i*th Predicted dimensionless moisture ratio
$MR_{exp,i}$:	*i*th Experimental dimensionless moisture ratio
n_o:	Number of observations
n_c:	Number of constants
P:	Microwave power, [W]
T_{in}:	The inlet temperature, [^{o}C]
T_{out}:	The outlet temperature, [^{o}C]
r:	Determination coefficient
Q:	The solar power received by the collector, [W]
t:	drying time, [h]
V:	The speed of the air flow, [m s^{-1}]
ΔE:	Total color change parameter
$\dot{m}$:	The mass flow rate, [kg s^{-1}]
ρ:	Density, [kg m^{-3}]
μ:	Thermal efficiency
χ^2:	Mean squared deviation

REFERENCES

1. Aktaş, M. and Kara, M. Ç. 2013. Sliced Kiwi Drying in a Solar Energy and Heat Pump Dryer. *J. Fac. Eng. Archit. Gaz.*, **28(4):** 733-741.
2. Aktaş, M., Şevik, S., Doğan, H. and Öztürk, M. 2012. Drying of Tomato in a Photovoltaic and Thermal Solar-Powered Continuous Dryer. *J. Agric. Sci.*, **18(4):** 287-298.
3. Alibas, İ. 2012. Selection of the Best Suitable Thin-Layer Drying Mathematical Model for Vacuum Dried Red Chili Pepper. *JBES*, **6(17):** 161-170.
4. Arda, S. O. 2016. Experimentally Investigation of Behaviour of Drying by Using Combined Microwave Belt and Solar Energy Dryer. M.Sc. Thesis, Namık Kemal University, Turkey.
5. Bala, B. K. and Hossain, M. A. 2012. Solar Drying of Fishery Products. In: Solar drying: Fundamentals, Applications and Innovations, eds: By Hii, C. L., S. P. Ong, S. V. Jangam and A. S. Mujumdar, ISBN: 978-981-08-6759-1, Published in Singapore, pp. 95-110.
6. Bingöl, G. and Devres, Y. O. 2010. *Fundamentals of Drying Technologies in Food Processing.* Istanbul Chamber of Industry -İtü, III, İstanbul/Turkey.
7. Boldor, D., Danders, T. H., Swartzel, K. R. and Farkas, B. E. 2005. A Model for Temperature and Moisture Distribution during Continuous Microwave Drying. *J. Food Process Eng.*, **28:** 68-87.
8. Bulut, H. and Durmaz, A. F. 2006. Design, Manufacturing and Experimental Analysis of an Air Solar Collector, UGHEK'2006: I. *National Solar and Hydrogen Energy Congress*, Turkey, June, 21-23, PP. 168-175.
9. Çelen, S., Kahveci, K., Akyol, U. and Haksever, A. 2010. Drying behavior of cultured mushrooms. *J. Food Process. Preserv.*, **34(1):** 27-42.
10. Datta, A. K., Geedipalli, S. S. R. and Almeida, M. F. 2005. Microwave Combination Heating. *Food Technol.*, **59:** 36-40.
11. Dimitrios, T., Achilleas, B., Alexandros, V., Dionysios, T., Andronikos, F. and Dionissios, M. 2014. An Experimental Study on Convective Drying of Quince. *Revista Romana de Inginerie Civila*, **5(1):** 79.
12. Dinani, S. T., Hamdami, N., Shahedi, M. and Havet, M. 2014. Mathematical Modeling of Hot Air/ElectroHydroDynamic (EHD) Drying Kinetics of Mushroom Slices. *Energ. Convers. Manage.*, **86:** 70-80.
13. Ekow, A.E., Haile, M. A., John, O. and Narku, E. F. 2013. Microwave-Vacuum Drying Effect on Drying Kinetics, Lycopene and Ascorbic Acid Content of Tomato Slices. *J. Stored Prod. Postharvest Res.*, **4(1):** 11 – 22.
14. Ertekin, C. and Yaldız, O. 2010. Thin Layer Drying of Sliced Squash by Forced Convection. *Presented at 17th World Congress of the International Commission of Agricultural and Biosystems Engineering (CIGR)*, Canada, June 13-17, PP. 1-10.
15. Jairaj, K. S., Singh, S. P. and Srikant, K. 2009. A Review of Solar Dryers Developed for Grape Drying. *Sol. Energ.*, **83(9):** 1698-1712.
16. Kahveci, K. and Cihan, A. 2008. Drying of Food Materials. In: "*Transport Phenomena*". Nova Science, United States, PP. 65-144.
17. Karaaslan, S. and Tunçer, İ. K. 2009. Investigating of Drying Characteristics and Determining of a Drying Model for Microwave-Fan Assisted Convection

Drying of Red Pepper. *KSU J. Nat. Sci.*, **12(2):** 9-16.

18. Kutlu, N., İşci, A., and Demirkol, Ö. Ş. 2015. Thin Layer Drying Models in Food Systems. *Food,* **40(1):** 39-46.
19. Litvin, S., Mannheim, C. H. and Miltz, J. 1998. Dehydration of Carrots by a Combination of Freeze Drying, Microwave Heating and Air or Vacuum Drying. *J. Food Eng.,* **36:** 103-111.
20. Mazandarani, Z., Aghajani, N., Daraei Garmakhany, A., Bani Ardalan, M. J. and Nouri, M. 2017. Mathematical Modeling of Thin Layer Drying of Pomegranate (Punica granatum L.) Arils: Various Drying Methods. *J. Agr. Sci. Tech.*, **19:** 1527-1537.
21. Metaxas, R. C. and Meredith, R. J. 1983. *Industrial Microwave Heating.* Peter Peregrinus Ltd, London.
22. Mohammadi, B., Busaleyki, S., Modarres, R., Yarionsorudi, E., Fojlaley, M. and Andik, S. 2014. Investigation of Microwave Application in Agricultural Production Drying. *IJTR*, **2(1):** 69-72.
23. Mujumdar, A. S. and Zhonghua, W. 2008. Thermal Drying Technologies Cost Effective Innovation Aided by Mathematical Modeling Approach. *Dry. Technol.*, **26:** 145-153.
24. Polatcı, H. and Tarhan, S. 2009. The Effects of Various Drying Methods on the Drying Time and Quality of Basil (*Ocimum basilicum*). *JAFAG*, **26(1):** 61-70.
25. Puligundla, P., Abdullah, S. A., Choi, W., Jun, S., Oh, S. and Ko, S. 2013. Potentials of Microwave Heating Technology for Select Food Processing Applications - a Brief Overview and Update. *J. Food Process Technol.*, **4(11):** 278.
26. Rabha, D. K., Muthukumar, P. and Somayaji, C. 2017. Energy and Exergy Analyses of the
27. Safary, M. and Chayjan, R. A. 2016. Optimization of Almond Kernels Drying under Infraredvacuum Condition with Microwave Pretreatment using Response Surface Method and Genetic Algorithm. *J. Agr. Sci. Tech.*, **18:** 1543-1556.
28. Solar Drying Processes of Ghost Chilli Pepper and Ginger. *Renew. Energ*., **105:** 764-773.
29. Soleimanifard, S., Shahedi, M., Emam-Djomeh, Z. and Askari, G. R. 2018. Investigating Textural and Physical Properties of Microwave-Baked Cupcake. *J. Agr. Sci. Tech.,* **20:** 265-276.
30. Soysal, Y., Ayhan Z, Esturk, O. and Arikan, M. F. 2009. Intermittent Microwave–Convective Drying of Red Pepper: Ddrying Kinetics, Physical (Colour and Texture) and Sensory Quality. *Bioprocess Eng.*, **103:** 455-463.
31. Tosun, N., Bayındır, H. and Aydın, H. 2009. A Research on the Creation of Multifunctional
32. Simha, P., Mathew, M. and Ganesapillai, M. 2016. Empirical Modeling of Drying Kinetics and Microwave Assisted extraction of Bioactive Compounds from *Adathoda vasica* and *Cymbopogon citratus. Alexandria Eng. J.,* **55(1):** 141-150.
33. Solar Drying System in Diyarbakir Province. *Presented at Vth. Renewable Energy Resources Symposium*, June 19-20**,** Turkey, PP. 84-89.
34. Ulloa, J. A., Escalona, H. and Diaz, L. 2008. Colour Behaviour on Mango (*Mangifera indica*) Slices Self Stabilized in Glass Jars by Hurdle Technology during Storage. *Afr. J. Biotechnol.*, **7(4):** 487-494.
35. Zang, M., Tang, J., Mujumdar, A. S. and Wang, S. 2006. Trends in Microwave Related Drying of Fruits and Vegetables. *Trends Food Sci. Technol*., **17**: 524-534.
36. Zarein, M., Samadi, S. H. and Ghobadian, B. 2015. Investigation of Microwave Dryer Effect on Energy Efficiency during Drying of Apple Slices. *J. Saudi Soc. Agric. Sci.*, **14:** 41–47.
37. Zomorodian, A. and Moradi, M., 2010. Mathematical Modeling of Forced Convection Thin Layer Solar Drying for *Cuminum cyminum*. *J. Agr. Sci. Tech.,* **12:** 401-408.
38. Wang, W. C. and Sastry S. K. 2000. Effects of Thermal and Electrothermal Pretreatments on Hot Air Drying Rate of Vegetable Tissue. *J. Food Process Eng.*, **23(4):** 299-319.
39. Workneh, T. S., Oke, M. O. 2012. The Influence of the Combined Microwave Power and Hot Air Ventilation on the Drying Kinetics and Color, Quality of Tomato Slices. *Afr. J. Biotechnol.,* **11(87):** 15353-15364.

طراحی دستگاه خشک کن هیبریدی میکروویو-خورشیدی نیمکره ای و نحوه خشک کردن کدوی سبز

س. شلن، و س. اگوز آردا

چکیده

در این پژوهش، عملکرد یک دستگاه خشک کن هیبریدی میکروویو-خورشیدی که اخیرا طراحی شده بود بررسی شد. خشک کردن با کمک انرژی خورشیدی و خشک کن نقاله میکروویوی انجام شد. با استفاده از یک دستگاه جمع کننده(collector) که برای افزایش کارآیی انرژی خورشیدی به شکل نیمکره طراحی شده بود، هوای گرم تولید شد و از یک تونل با سرعت ۳ متر در ثانیه با مصرف توان میکروویوی ۰/۷ کیلو وات، ۱ کیلو وات، و ۱/۴ کیلووات گذر داده شد و نحوه خشک شدن ورقه هایی از کدوی سبز با ضخامت ۵، ۱۰ و ۱۵ میلی متر بررسی شد. در آخر فرایند خشک کردن، مدت خشک کردن، تغییرات رنگ محصول خشک شده، مصرف انرژی، کارآیی دستگاه جمع کننده، و مدلسازی از خشک کردن تعیین شد. با درنظر گرفتن زمان لازم برای خشک کردن ورقه های کدوی سبز تا رسیدن به 10±1٪ محتوای رطوبتی و مقدار مصرف انرژی برق، مناسبترین نتایج از شرایطی به دست آمد که در آن توان میکروویو ۱ کیلو وات بود و سرعت هوا برابر ۰/۲۴۵ متر در دقیقه و ضخامت ورقه کدو ۵ میلی متر و جمعا متناظر با انرژی کل معادل ۱/۱۴۳ کیلووات ساعت بود. کارآیی دستگاه جمع کننده در شرایط محیطی آزمایش ما در حد ۲۴/۳٪ محاسبه شد.