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Energy economy and kinetic investigation of sugar cube dehydration using microwave supplemented with thermal imaging

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Abstract

High energy and time consumption in the dehydration of sugar cubes hinder its industrial commercialization. Microwave is employed to overcome the drawbacks of hot air drying. For microwave power 880 W, pulsing ratios 1.5, 2.5, 4.5, and 10 were applied to prevent thermal runaway and probable melting and caramelization. In order to monitor the spatial thermal variation of sugar cubes, thermal imaging was performed. Maximum effective diffusivity was measured to be 9.0905×10^{-8} m^2/s, which belongs to pulsing ratio 2.5 and is 16 times larger than when hot air is used. Furthermore, the minimum specific energy consumption and minimum energy cost were calculated to be 314,192.45 J/g H_2O and 0.179×10^{-3} \$/g, respectively, which found in pulsing ratio 2.5. Technically speaking, regarding the critical temperatures of sugar cubes and energy economy, the study suggests pulsing ratio 2.5 for sugar cube dehydration using microwave power 880 W.

Practical applications

Sugar cube production line consists of several unit operations. Dehydration is the last operation commonly known as the major concern in industry due to high level of quality issues and energy aspects. At present, hot air drying is the common method in plants and is highly dependent on thermal conductivity of cubes which is very low. This method exerts notable costs to producers. Microwave technology as a solution is investigated in this research. Influencing parameters such as diffusivity, energy consumption, economy of energy, and kinetics are experimentally assessed and described. Based on the results obtained, the industry would have a full perception of using microwave radiation as a substitute for conventional hot air drying in order to resolve the challenges of energy, time, and costs.

1 | INTRODUCTION

Sucrose commonly named as sugar is found in numerous plant species and is commercially produced from sugar beets or sugar canes. Sugar cube, as used widely in different parts of the world, is also produced from wetting and pressing sugar crystals (Akosman, 2004). These compressed sugar crystals are then dehydrated to avoid the cube conglutination (Skočilas, Solnař, & Aidossuly, 2016). Dehydration is performed in drying process where the different driving forces for moisture transport are developed from the inside to the outside of the heated material. In this way, vapor pressure difference, concentration difference, temperature difference, and capillary force within the

Nomenclature: P, microwave power output (W); C_{PW}, specific heat of water (4.186 J/g °C); C_{Pg}, specific heat of glass container (0.55 J/g °C); M_W, mass of water (g); M_C, mass of container (g); M_s, mass of dry matter (g); T_0, ambient temperature (°C); T_1, initial temperature of water (°C); T_2, final temperature of water (°C); MR, moisture ratio; DR, drying rate (kg water/kg dry matter/s); M, moisture content of product at any time of drying process (dry basis); M_i, initial moisture content of product (dry basis); M_e, moisture balance (dry basis); M_t, moisture content of product at t time of drying process (dry basis); $M_{t+\Delta t}$, moisture content of product at $t + \Delta t$ time of drying process (dry basis); M_f, final moisture content of product (dry basis); PR, pulsing ratio; t_{on}, on time cycle microwave power (s); t_{off}, off time cycle microwave power (s); D_e, effective diffusivity (m^2/s); L, half the thickness of slab sample (m); n, positive integer; SEC, specific energy consumption (J/g H_2O); E, energy consumption of microwave (J); t, drying time (s); t_h, microwave heating time (s); t_r, microwave radiation time (s).

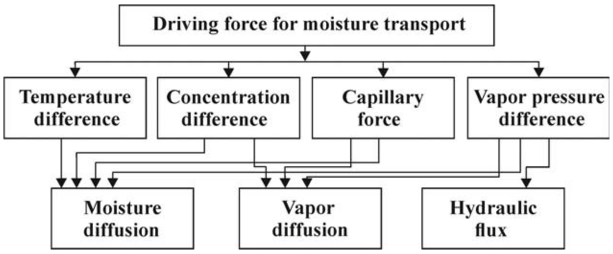

FIGURE 1 Mechanism of moisture transport inside materials during drying process

product supply the required force for water removal and drive water toward the product surface by a combination of vapor diffusion, moisture diffusion, and hydraulic flux. Surface moisture is then vaporized, and this process is repeated until drying completed (Figure 1) (Rahman, 2007; Wang, Zhang, & Mujumdar, 2014).

Hot air flow is a typical technique for drying sugar cubes (Skočilas et al., 2016). In this method, dehydration starts from product surface through convective heat transfer. The heat is then transferred inside the product through conduction (Kumar, Mujumdar, & Koran, 1990; Mujumdar, 2015). Since biological materials have low thermal conductivity, heat transfer in hot air flow method, due to strong dependence on conduction, faces some drawbacks (Akosman, 2004; Kocabiyik & Tezer, 2009). Nowadays, for promoting heat transfer systems in drying industry, new techniques such as microwave dryers are demanded (Sorour & El-Mesery, 2014). Microwaves are the form of electromagnetic waves within the frequency band of 300 MHz to 300 GHz and wavelengths ranging from 1 m to 1 mm, respectively (Metaxas & Meredith, 1983). These waves penetrate into the product and cause volumetric heating as a result of dipolar relaxation and ionic conduction. In dipolar relaxation, polar molecules such as water molecules subjected to electrical field whose direction changes 2.45×10^9 times per second (according to microwave frequency, 2.45 GHz). Polar molecular rotation occurs with changes in electric field direction and leads to volumetric heat generation as a result of friction between rotating molecules. In ionic conduction, electrical field causes the ions to move towards the direction opposite to their own polarity. Eventually heat is generated due to the collision and friction between ions and molecules (Sahin & Sumnu, 2006).

Generally, the following four mechanisms have been proposed for improvement of heating systems and reduction of energy consumption in dryers (Kemp, 2012) that are advantageously applicable in microwave dryers contrary to hot air flow method: (a) preventing excessive drying and moisture vaporization; (b) preventing temperature increase in solid parts of the product; (c) decreasing the drying time; and (d) promoting dryer efficiency, e.g., controlling heat and energy loss. In hot air method, heat moves from product surface into the product and the surface dries excessively. Moreover, the solid part of the product, as well as the moisture, heats up and contributes to loss of energy. In contrast, microwave causes volumetric heating and generates a more uniform drying (Gowen, Abu-Ghannam, Frias, & Oliveira, 2006). A key feature of microwave is selective heating, and the water contained in the product is the essential element for microwave heating as it is dipolar component of product (Ratti, 2008; Zhang, Jiang, & Lim, 2010). Accordingly, energy losses in the exhaust of microwave dryer unlike hot air dryer are significantly controlled since air temperature inside the microwave oven chamber is kept consistent at room temperature during the drying process (USDA, 2013). Regarding the characteristics of heat transfer in microwave method, drying time is significantly reduced, promoting dried product quality because thermal damages to the product are directly proportional to temperature and heating time (Ahmed & Ramaswamy, 2007; Lin, Durance, & Scaman, 1998; Mousa & Farid, 2002). As mentioned, microwave heating offers many advantages, so there is a growing interest in industrial microwave systems (Meredith, 1998) in regard to microwave drying kinetics (Al-Harahsheh, Al-Muhtaseb, & Magee, 2009; Feng, Tang, & Cavalieri, 1999; Hazervazifeh, Moghaddam, & Nikbakht, 2016; Karaaslan & Tunçer, 2008; Özbek & Dadali, 2007; Sarimeseli, 2011), comparing kinetics of microwave drying with hot air drying (Arslan & Musa Özcan, 2010; Gowen, Abu-Ghannam, Frias, & Oliveira, 2008; Kardum, Sander, & Skansi, 2001) and energy consumption in microwave drying process (Alibas, 2007; Hazervazifeh, Nikbakht, & Moghaddam, 2016; Kassem, Shokr, El-Mahdy, Aboukarima, & Hamed, 2011; Motevali, Minaei, & Khoshtagaza, 2011; Motevali, Minaei, Khoshtaghaza, & Amirnejat, 2011; Sharma & Prasad, 2006; Zarein, Samadi, & Ghobadian, 2015). Results indicate that higher drying rate due to higher moisture diffusion is revealed in microwave drying method, leading finally to less energy consumption in comparison to hot air method.

Despite numerous studies on sugar production technologies, there are only a limited number of studies on sugar cube dehydration using mostly hot air flow method (Akosman, 2004; Skočilas et al., 2016). Sucrose melts and forms glucose and fructose anhydride (levulosan) at 160 °C, and caramelization of sucrose requires a temperature of about 200 °C. A caramelization reaction occurs when sugars are heated in the absence of water (Deman, 1999). In microwave-drying process at a fixed level of microwave power, when almost free water of product is vaporized, product temperature rises sharply; this is known as thermal runaway, due to an increase in the specific microwave energy input (ratio of microwave energy to unit mass of wet product) and a decrease in the specific heat of the product (Botha, Oliveira, & Ahrné, 2012; Figiel, 2010). Therefore, there is a potential risk of thermal runaway in sugar cube drying process using microwave. Pulsed radiation is often used to control product temperature and overheating at high and fixed level of microwave powers. When there is no radiation, variation of product temperature occurred at the radiation time is balanced due to heat transfer, and because of reduced hot spots on the product, temperature differences are minimized. Thus, pulsed radiation controls the product temperature and enhances the quality of the dried products (Yang & Gunasekaran, 2004). Moreover, pulsed radiation is found to be more energy efficient than continuous radiation (Sharifian, Mohammad Nikbakht, Arefi, & Modarres Motlagh, 2015). Pulsed heating model is extensively studied (Chamchong & Datta, 1999; Changrue, Orsat, & Raghavan, 2008; Gunasekaran, 1990; Gunasekaran & Yang, 2007;

TABLE 1 On and off time cycle microwave power at different pulsing ratios

Pulsing ratio	On time (s)	Off time (s)
1.5	22	7
2.5	12	17
4.5	6	23
10	3	27

Soysal, Ayhan, Eştürk, & Arıkan, 2009). The present study furnishes detailed information on the kinetics, energy analysis, economic analysis, and temperature profiles of microwave sugar cube dehydration. Effective diffusivity and optimal pulsing ratio for sugar cube dehydration process are measured.

2 | MATERIALS AND METHODS

2.1 | Sample preparation

Sugar cubes (1.5 cm) before dehydration were prepared from a sugar factory in West Azerbaijan Province, Iran, and stored at 4 °C in a closed container to avoid demoisturization. Average initial moisture content of the samples in three replications at the temperature of 70 °C and vacuum pressure of 1 bar was determined to be 3.23% (wet basis).

2.2 | Equipment

Sugar cubes were dried on turntable (4 rpm) of a domestic microwave oven operating at the frequency 2.45 GHz with pulsed radiation.

2.3 | Actual microwave power output of a magnetron

Actual microwave power output of a magnetron was measured with three replications in accordance with standard IEC (International Electrotechnical Commission). Therefore, 1,000 g water in a 580 g glass container was subjected to continuous microwave radiation for 60 s. Before heating, temperature of the container and water was balanced and measured to be 23 °C. After heating, water temperature reached 34.7 °C and the output microwave power from the magnetron was determined to be 880 W using the following equation (IEC, 1999):

$$P=\frac{C_{PW}m_w(T_2-T_1)+C_{Pg}m_c(T_2-T_0)}{t_h} \quad (1)$$

2.4 | Pulsing ratio (on–off ratio)

Pulsing ratio is expressed as the following equation (Sharifian, Motlagh, & Nikbakht, 2015) and summarized in Table 1:

$$PR=\frac{(t_{on}\ +\ t_{off})}{t_{on}} \quad (2)$$

2.5 | Experimental procedure

Before experimentation, samples in the closed container were taken out of the fridge to adapt with ambient temperature. Temperature and relative humidity of the ambient were 18 °C and 50%, respectively. Experiments were conducted in three treatments with the microwave power of 880 W and pulsing ratios of 1.5, 2.5, 4.5, and 10, in three replications, where 57 g sugar cubes were dried until sample moisture dropped to 0.06% (wet basis). Moreover, drying kinetics of sugar cubes including moisture ratio, drying rate, and effective diffusivity was examined. Sugar cube temperature, consistent with drying kinetic phases, was analyzed by taking thermal images.

2.6 | Moisture ratio and drying rate

Moisture ratio is essential for analysis and controlling the drying process. Drying rate as the amount of moisture removal from the product per unit of time is also an important parameter in the drying process. Moisture ratio and drying rate (kg water/(kg dry matter min)) are defined by the following equations (Hazervazifeh, Moghaddam, et al., 2016; Kaya & Aydın, 2009):

$$MR=\frac{M-M_e}{M_i-M_e} \quad (3)$$

$$DR=\frac{M_t-M_{t+\Delta t}}{\Delta t} \quad (4)$$

2.7 | Thermal imaging

To visualize spatial variation of temperature in sugar cubes during microwave drying according to the drying kinetic phases, a thermal imaging camera (Nippon Avionics Co., Ltd., Japan) with an accuracy of 0.01 °C was used to record thermal image profiles where immediately after microwave heating thermal images were taken. Thermal imaging is an industrial standard tool for assessing temperature distribution of products at the end of the microwave heating process (Pitchai, 2011). Mean temperature of samples was measured in each replication as microwave heating is nonuniform, and then, average value of three replication in each treatment was analyzed (Vadivambal & Jayas, 2010).

2.8 | Moisture diffusion

The proper model for describing water movement in the solid substance during the drying process is Fick's second law of diffusion (Özbek & Dadali, 2007; Skočilas et al., 2016). Diffusivity is calculated by comparing drying slope and the predicted equation from numerical or analytical solving of Fick's second law (Akosman, 2004). Fick's second law assuming constant effective diffusivity (D_e) is defined as follows:

$$\frac{\partial M}{\partial t}=D_e\nabla^2 M \quad (5)$$

It is expanded to the following equation in three-dimensional state.

TABLE 2 Radiation time during drying process at different pulsing ratios

Pulsing ratio	Drying time (s)	Radiation time (s) × 10^2
2.5	1,560	64,551.724
4.5	5,100	105,517.241
10	14,450	149,482.759

$$\frac{\partial M}{\partial t}=D_e\left(\frac{\partial^2 M}{\partial x^2}+\frac{\partial^2 M}{\partial y^2}+\frac{\partial^2 M}{\partial z^2}\right) \tag{6}$$

As sugar cube transfers moisture in all faces and hence the governing equation must take into consideration of a three dimensional diffusion, Fick's equation was solved in *x*, *y*, and *z*-axes. By separation of variables, the 3D solution can be written in the form of the following equation:

$$MR(x,y,z,t)=X(x,t)Y(y,t)Z(z,t) \tag{7}$$

The solution of *x* component of Equation 6 when the external resistance is negligible would be (Rossello, Canellas, Simal, & Berna, 1992):

$$MR^x = 2\sum_{n=0}^{\infty}\frac{(-1)^n}{(2n+1)\frac{\pi}{2}}\exp\left[\frac{-(2n+1)^2\pi^2}{4}\frac{D_e t}{L^2}\right]\cos\left((2n+1)\frac{\pi x}{2L}\right) \tag{8}$$

Similarly, one can yield to solutions in *y*-axis and *z*-axis. In case of prolonged drying process, the first term of series solution ($n=0$) yields a good estimation of moisture ratio (Tütüncü & Labuza, 1996). However, in order to have the influence of sentences of the above series, a code was developed in MATLAB. The code estimated first the best D_e according to least RMSE of MR values with the experimental MRs. Then, the same procedure was repeated with the extended sentences of the solution series (Singh, Kumar, & Gupta, 2007). In this computation, the first six sentences of the series were analyzed and the average of the D_e obtained were calculated and reported.

2.9 | Energy analysis

Energy consumption during the drying process was evaluated with specific energy consumption (SEC) (Soysal, Öztekin, & Eren, 2006; Varith, Dijkanarukkul, Achariyaviriya, & Achariyaviriya, 2007):

$$SEC=\frac{E}{M_s(M_i-M_f)} \tag{9}$$

Energy consumption in microwave dryers can be computed as follows (Ozkan, Akbudak, & Akbudak, 2007):

$$E=Pt_r \tag{10}$$

Radiation time (t_r) at different pulsing ratios is detailed in Table 2.

2.9.1 | Energy costs

Relative costs of energy sources tend to reflect the primary energy use. The cost of electric power generated by fossil fuels is determined as 64.8 \$/MWh = 18 \$/GJ. It is important to note that the energy prices can fluctuate widely. Nevertheless, in the case of power generation with hydro-electricity instead of fossil fuels, dramatic decline in energy costs can be seen (Kemp, 2012).

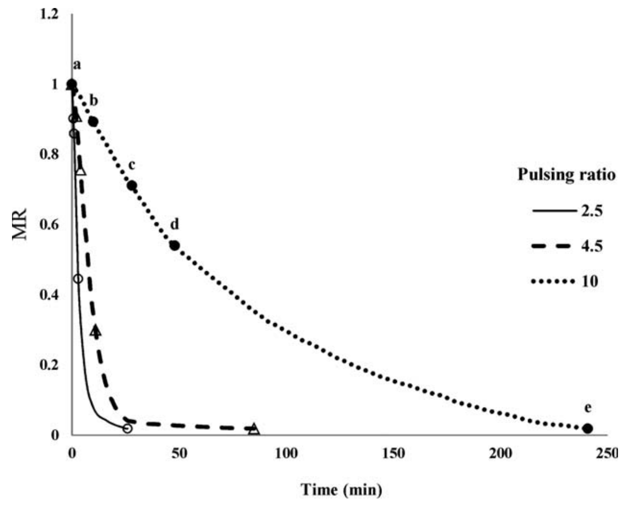

FIGURE 2 Variation of moisture ratio (MR) at different pulsing ratios

3 | RESULT AND DISCUSSION

Kinetics of sugar cube drying was analyzed in terms of moisture ratio, drying rate, and effective diffusivity in pulsing ratios of 1.5, 2.5, 4.5, and 10. However, at pulsing ratio 1.5, sugar cubes melted and the process stopped.

3.1 | Moisture ratio and drying rate

Three distinct phases were observed in microwave drying kinetics of sugar cubes (Figure 2). Similar results have been reported for potato (Bouraoui, Richard, & Durance, 1994), mint leaf (Özbek & Dadali, 2007), tomato (Al-Harahsheh et al., 2009), fig (Sharifian et al., 2015), and apple (Hazervazifeh, Moghaddam, et al., 2016).

1. Warming up period: product temperature increases with time and dehydration begins when vapor pressure inside the product exceeds the ambient vapor pressure (lines a and b in Figures 2 and 3).
2. Constant rate period: results demonstrate that the drying rate tends to be constant after a short warming up period (lines b and c in Figures 2 and 3).
3. Falling rate period: in this phase, evaporation rate decreases with time and the slop of the drying rate curve becomes less steep (lines c–e in Figures 2 and 3). This is because decreased moisture content of the product gives rise to two simultaneous incidents. On one hand, decreased dielectric constant ε′ and dielectric loss factor ε″ lead to considerable decrease in microwave energy absorption and heat generation. On the other hand, intense resistance to moisture removal as a result of dried product layers, and a reduction in concentration difference, and vapor pressure difference as driving forces (Figure 1), contribute to decreasing the drying rate. This is in agreement with findings of Pereira, Marsaioli, and Ahrné (2007)

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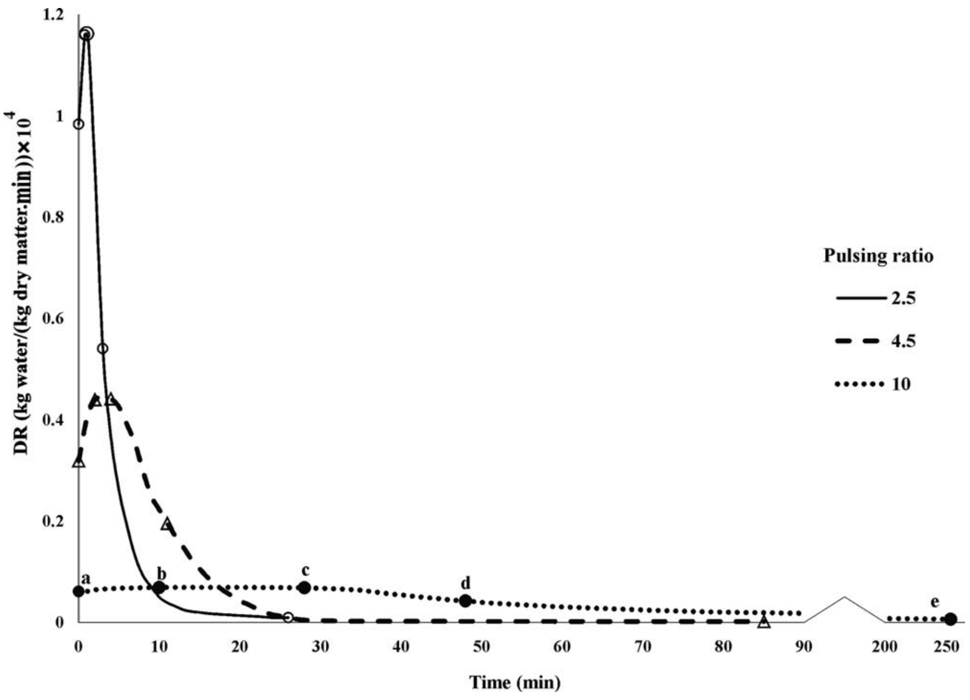

FIGURE 3 Variation of drying rate (DR) at different pulsing ratios

(Pereira et al., 2007). Our results indicate that the longest time for drying occurs in the falling rate period.

Results show that kinetics of sugar cubes in microwave drying can be divided into two other phases after the warming up period. The first is rapid rate period, which regarding the previous division, includes the constant rate period and falling rate period with steep slope, whereby most of the free moisture is dehydrated. Duration of this phase is determined by drying rate curve and continues as long as the curve is a straight line. Rapid rate period is marked off in all treatments at point *d* with $R^2 = 0.98$ (lines b–d in Figure 2). The second is falling rate period with less steep slope that continues to the end of the process (lines d and e in Figure 2). Pulsing ratio influences over the drying rate in the sense that decreased pulsing ratio prolongs microwave radiation and hence heat generation tends to increase. Thus, vapor pressure inside the product becomes larger than its surface (Figure 1), leading to increased drying rate and decreased drying time (Figure 3). For instance, at pulsing ratios 2.5, 4.5, and 10, maximum drying rates of

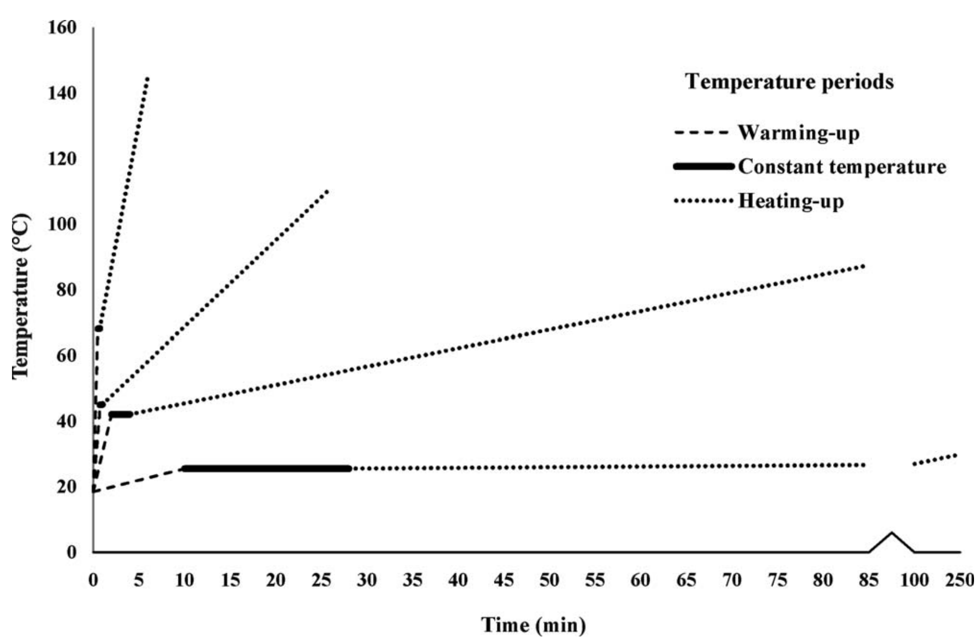

FIGURE 4 Variation of sugar cube temperature in microwave drying at different pulsing ratios

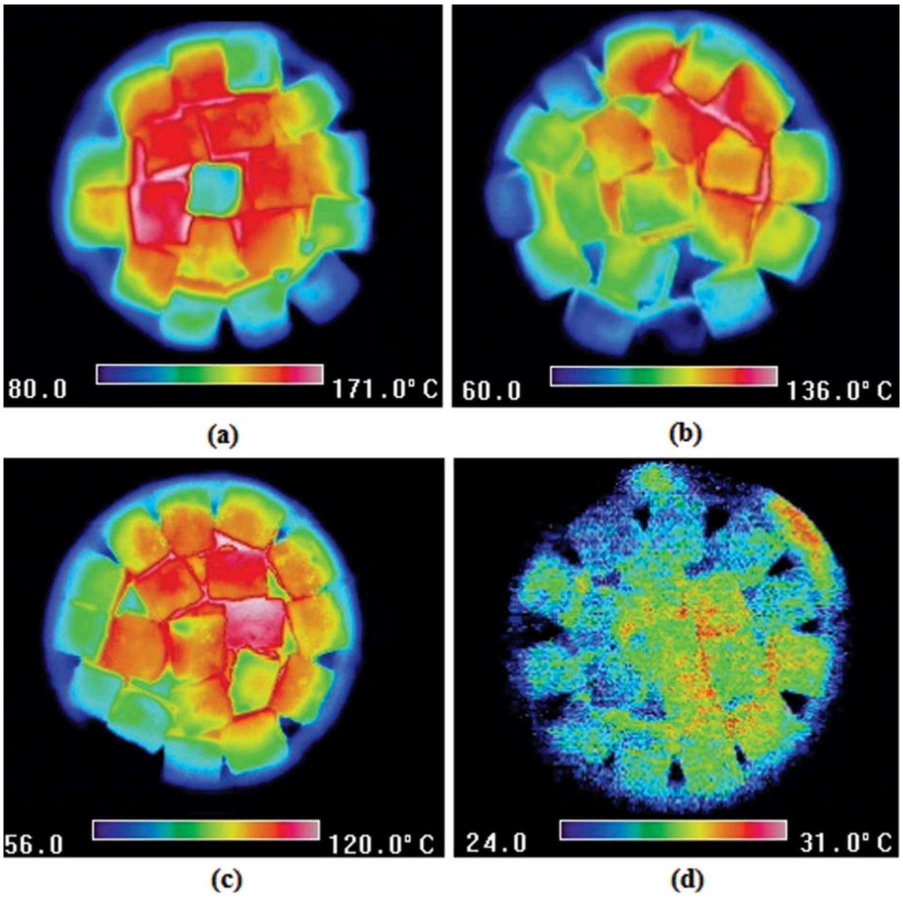

FIGURE 5 Temperature of sugar cubs at the end of heating-up period at different pulsing ratios: (a) 1.5, (b) 2.5, (c) 4.5, and (d) 10

1.16×10^{-4}, 4.44×10^{-5}, and 6.87×10^{-6}/s and process time of 26, 85, and 241 min were recorded respectively. This is in agreement with findings of Arikan, Ayhan, Soysal, and Esturk (2012) and Figiel (2010) (Arikan et al., 2012; Figiel, 2010).

3.2 | Temperature variation of sugar cubes during microwave drying

Temperature variations of sugar cubes during microwave drying at four pulsing ratios were assessed in each treatment through thermal imaging at the end of warming up, constant rate, and falling rate periods. Results revealed three temperature periods consistent with drying kinetics (Figure 4). Results by Clary, Wang, and Petrucci (2005), Ahrné, Pereira, Staack, and Floberg (2007) and Sharifian et al. (2012) confirm our findings (Ahrné et al., 2007; Clary et al., 2005; Sharifian et al., 2012).

1. Warming-up period: microwave reacts to sugar cubes and produces volumetric heating which raises product temperature.
2. Constant temperature period, which is consistent with constant drying rate period: sugar cubes temperature remains nearly constant as moisture evaporates from the product surface and cooling by moisture evaporation is balanced with microwave heating. In contrast, a great deal of heat energy from microwave energy conversion is used for moisture vaporization and phase change of water from liquid to vapor.
3. Heating-up period: in this period, energy for moisture vaporization becomes much less than heat energy from microwave energy conversion due to low moisture content of the product. Therefore, water temperature is likely to rise to boiling temperature. Though dielectric loss factor decreases with moisture removal and conversion of microwave energy into heat reduces, product temperature rises and makes sugar cubes more likely to melt. Results showed that reduced pulsing ratio leads to shorter constant temperature period and steeper slope in warming-up and heating-up periods.

At pulsing ratios 1.5, 2.5, 4.5, and 10, the mean temperature of sugar cubes at the end of falling rate period was found to be 145.13, 110.81, 87.43, and 29.69 °C, respectively. However, at pulsing ratio 1.5, the temperature of some sugar cubes reached above 160 °C and sugar cubes melted and the process stopped after 6 min. Figure 5 represents thermal imaging at the end of falling rate period of one replication at different pulsing ratios.

3.3 | Effective diffusivity

Effective diffusivities are presented in Table 3 for microwave drying of sugar cubes at different pulsing ratios using Equation 6.

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TABLE 3 Effective diffusivity of sugar cub in microwave drying at different pulsing ratios and maximum effective diffusivity of sugar cub in hot air drying (Akosman, 2004) and (Skočilas et al., 2016)

Drying method	Pulsing ratio	Temperature (°C)	Air velocity (m/s)	De × 10^6 (m^2/s)
	2.5			0.090905
Microwave	4.5	–	–	0.04040
	10			0.00404
Hot air (Akosman, 2004)	–	95	0.56	0.00581
Hot air (Skočilas et al., 2016)	–	80	1.5	0.0023 ± 0.00013

TABLE 4 Specific energy consumption and energy cost at different pulsing ratios

Pulsing ratio	Specific energy consumption (J/g H_2O)	Energy cost × 10^3 ($/g)
2.5	314,192.45	0.179
4.5	513,583.81	0.293
10	727,577.07	0.415

Effective diffusivity of sugar cubes in microwave drying, as compared to hot airflow drying, increases 16-fold (Microwave method at 2.5 pulsing ratio compared to Akosman, 2004 in Table 3) due to differences in heat transfer mechanism. In microwave drying, volumetric heating occurs inside the product and increases vapor pressure gradient, mass transfer rate, as well as effective diffusivity, but in hot airflow drying, heat penetrates from the surface to the product and heat transfer relies on heat transfer coefficient of the product. Thus, heat and mass transfer is slow. Pulsing ratio has an undeniable effect on effective diffusivity. It is evident that as pulsing ratio increases, effective diffusivity decreases where pulsing ratio of 10 lower D_e is obtained compared to hot air method.

3.4 | Energy analysis

Specific energy consumption in microwave drying was examined at pulsing ratios of 1.5, 2.5, and 10 (Table 4). Since in each experiment, mass of dry solid (M_s), initial moisture content (M_i), and the final moisture content (M_f) were constant, specific energy consumption would depend on the performance of the heat source, i.e., $E(Pt_r)$ term. Thus, as pulsing ratio decreases, process time decreases and the result of multiplying Pt_r parameters drops, leading finally to decreased specific energy consumption. This is because of increased vapor pressure gradient and fast drying process as a result of prolonged microwave radiation period in Equation 2. In contrast, decreased pulsing ratio decreases energy consumption and relevant costs. Minimum costs were observed for pulsing ratio 2.5 (Table 4).

Accordingly, in microwave drying of sugar cubes at power 880 W, continuous radiation and pulsed radiation at pulsing ratio less than 2.5 are not suggested because of critical temperatures of sucrose. Moreover, regarding the quality of dried sugar cubes, specific energy consumption, and energy economy, the study corroborates the pulsing ratio of 2.5 for microwave power of 880 W.

4 | CONCLUSIONS

Owing to documented ability of microwave radiation in the drying of food commodities, and regarding the low thermal conductivity of most agricultural products, microwave dehydration of sugar cubes is studied. Energy, temperature variation, and kinetic attributes are discussed to get a full perception of the process. Results indicated that at pulsing ratio 1.5, the temperature of some sugar cubes reached above 160°C and sugar cubes melted and hence the process stopped. Moreover, results elucidated three distinct temperature periods consistent with drying kinetics. Kinetic study of the process proved that sugar cube drying with microwave goes through warming up, constant rate, and falling rate periods. It was revealed a notable increase of diffusivity compared with hot air flow, having its maximum value around 9.0905×10^{-8} m^2/s when the pulsing ratio of 2.5 was applied to the radiation. Minimum specific energy consumption in microwave drying of cubes was calculated to be 314,192.45 J/g H_2O at the mentioned pulsing ratio. Energy economic estimation also proved that the minimum energy cost, 0.179×10^{-3} $/g, is achieved at such condition.

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