MICROWAVE DEHYDRATION OF SUGAR CUBE: THERMOPHYSICAL INVESTIGATION AND FINITE ELEMENT SOLUTION
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آبزدایی از حبه قند با مایکروویو: بررسی ترموفیزیکی و حل المان محدود

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***Keywords:** sugar cube, finite element method, temperature distribution, moisture removal pattern, colour analysis.*

ABSTRACT

Finite element numerical solution was employed to solve coupled model of electromagnetic, heat and mass transfer phenomena in microwave dehydration of sugar cube. For microwave power 880 W, pulsing ratios 1.5, 2.5, 4.5 and 10 were applied to prevent thermal runaway. Colour quality of dried sugar cubes was assessed by calculating whiteness, yellowness and total colour difference. Results revealed that uniform heating as a major issue of drying was improved with pulsing ratio. Moreover, low pulsing ratios yielded to lower colour quality. Thus, preferable pulsing ratio based on heating uniformity and colour quality of dried sugar cube is 10.

چکیده

برای حل مدل ترکیبی الکترومغناطیس، انتقال حرارت و جرم در فرآیند آبزدایی از حبه قند با استفاده از مایکروویوازروش عددی المان محدود استفاده گردید. توان مایکروویو 880 W انتخاب شد که برای جلوگیری از افزایش بیش از حد دمای حبه قندها در طی فرآیند خشک کردن، نسبت های پالسی 1/5، 2/5، 4/5 و 10 اعمال گردید. کیفیت رنگ محصول خشک شده با محاسبه سفیدی، زردی و اختلاف رنگ کل مورد بررسی قرار گرفت . نتایج نشان داد گرمایش یکنواخت به عنوان یک موضوع مهم در فرآیند خشک کردن، با افزایش نسبت پالسی، بهبود می یابد. از طرفی دیگر نسبت پالسی کم، سبب کاهش کیفیت رنگ محصول خشک شده م ی گردد. بنابراین نسبت پالسی مطلوب بر اساس گرمایش یکنواخت و کیفیت رنگ حبه قند خشک شده، 10 می‌باشد.

Nomenclature

PR	Pulsing ratio	**P_V**	Conversion of microwave power per unit volume (W m^{-3})
t_{On}	On time cycle microwave power, (s)	**f**	Frequency (Hz)
t_{Off}	Off time cycle microwave power, (s)	ε_0	Free space permittivity (8.85×10^{-12} Fm^{-1})
E	Electric field intensity (Vm^{-1})	ε'	Dielectric constant
H	Magnetic field intensity (Am^{-1})	ε''	Dielectric loss factor
D	Electric displacement (NV^{-1} m^{-1})	**D_e**	Effective diffusivity
B	Magnetic induction (T)	**c**	Water concentration (mol m^{-3})
μ	Permeability (Hm^{-1})	**x**	Depth from the surface of sample (m)
ε^*	Complex relative permittivity	**P(x)**	power dissipation value at depth x (W)
ρ	Density (kg m^{-3})	**P_0**	Incident power at the surface (W)
C_P	Specific heat capacity (J kg^{-1} K^{-1})	**β**	Attenuation constant (m^{-1})
T	Temperature (˚C)	**WI_{CIE}**	Whiteness index
t	Drying time (s)	**YI_{FC}**	Yellowness index
K	Thermal conductivity (W m^{-1} K^{-1})	**ΔE^***	Total colour difference with respect to undried sample
ω	Angular frequency (radians s^{-1})		

INTRODUCTION

Sucrose is commercially extracted from cane or beets and then refined to produce the white crystalline grains that is named sugar *(deMan, 1999)*. Sugar cube, is also produced from wetting and pressing sugar crystals. These compressed sugar crystals are then dehydrated to avoid the cube conglutination *(Skočllas et al., 2016)*. Hot air drying is a most common method for dehydrating sugar cubes *(Skočllas et al., 2016)*. In this method, heat transfer is strongly dependent on the conduction and considering the low thermal conductivity of the biological products, penetration of heat into the flesh is regarded as a major concern increasing the drying period. Therefore hot air flow drying of sugar cube faces major drawbacks such as long drying time and colour degradation of a dried product since thermal damages to the product is directly proportional to temperature and heating time *(Akosman, 2004; Kocabiyik and Tezer, 2009)*. The desire to eliminate these problems convinced researchers to seek new technologies such as microwave dryers to optimize the heat transfer systems *(Kassem et al., 2011)*. This method is gaining popularity in food processing, because of fast heating rate, efficient heat transfer, uniform temperature distribution and high product quality in comparison to conventional heating *(Hazervazifeh, Moghaddam, et al., 2016; Karaaslan and Tunçer, 2008)*. Microwaves are a form of electromagnetic waves within the frequency ranging from 300 MHz to 300GHz and wavelengths ranging from 1 m to 1 mm, respectively *(Metaxas and Meredith, 1983)*. These waves are not in the form of heat but, rather, a form of energy that the absorption of microwaves by a dielectric material results in the microwaves giving up their energy to the material, with a consequential rise in temperature. The two important mechanisms that explain heat generation in a material placed in a microwave field are ionic polarization and dipole rotation that are generally due to collisions between the ions of material and friction between the molecules of material heat is generated *(Singh and Heldman, 2001)*.

As mentioned before, microwave heating offers many advantages, so there is a growing interest in industrial microwave systems in respect to microwave heating simulation *(Knoerzer et al., 2008; Pitchai, 2011; Romano et al., 2005)*, comparing microwave drying with hot air drying *(Arslan and Musa Özcan, 2010; Gowen et al., 2008; Hazervazifeh, Nikbakht, et al., 2016)* temperature distribution analysis in microwave drying *(Knoerzer et al., 2008; Vadivambal and Jayas, 2010; Wang et al., 2008)*, colour analysis of products being dried by microwave *(Arslan and Musa Özcan, 2010; Botha et al., 2012; Celen and Kahveci, 2013)*.

Results in literature indicate that minimum drying time and higher drying rate is revealed in microwave drying in comparison to hot air method. Moreover, microwave drying presented better colour values in the dried products and the colour quality of the product deteriorates significantly with the increase of the microwave power. Furthermore results show that microwave heating is non-uniform and different factors affect the heating uniformity such as food shape and size, dielectric properties of food, microwave power and cycling.

Despite numerous studies on sugar production technologies, there is only a limited number of studies on sugar cube dehydration using mostly hot air flow method *(Akosman, 2004; Skočllas et al., 2016)*. Sucrose melts and forms glucose and fructose anhydride (Levulosan) at 160°C *(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 et al., 2012)*. Therefore, there is a potential risk of thermal runaway in sugar cube drying process using microwave. Cycling or pulsed radiation is often used to control product temperature and overheating at high and fixed level of microwave powers. Moreover, pulsed heating model is extensively studied *(Changrue et al., 2008; Gunasekaran and Yang, 2007; Soysal et al., 2009)*. The need for improvement in engineering design and process optimization for microwave drying has stimulated the development of computer simulation techniques to predict, electromagnetic field, temperature and moisture distribution in materials*(Kadem et al., 2014)*. Coupled electromagnetic and thermal PDE equations of three-dimensional coordinates with boundary conditions cannot be solved analytically and require iterative numerical methods *(Pitchai, 2011)*. Two methods mainly applied to model the heat transfer are finite difference method (FDM) and finite element method (FEM). FEM has been extensively used to solve the microwave heating process in food due to its flexibility in handling irregular geometrical configurations and material properties, depending on the temperature and moisture *(Romano et al., 2005)*.

The present study furnishes detailed information on the 3-D temperature distribution and moisture removal pattern of microwave sugar cube dehydration. Moreover, colour analysis of dried sugar cube was conducted to determine optimal pulsing ratio for microwave sugar cube dehydration.

MATERIAL AND METHODS

Sample preparation

Sugar cubes (1.5 cm) before dehydration were prepared by 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).

Equipment

Sugar cubes were dried with a domestic microwave oven operating at the frequency of 2.45 GHz with pulsed radiation.

Pulsing ratio (on-off ratio)

Pulsing ratio is expressed as Eq. 1*(Sharifian et al., 2012)* and summarized in table 1:

$$PR = \frac{(t_{On} + t_{Off})}{t_{On}} \tag{1}$$

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

Computer simulation

In this work, Maxwell equations for electromagnetic field were coupled with Fourier's law and Fick's second law for heat and mass transfer, respectively. Subsequently, the coupled model as a set of partial differential equations (PDE) is integrated by Finite Element Method (FEM). The package COMSOL Multiphysics 5.2 was used for the simulations *(Knoerzer et al., 2008; Navarrete et al., 2012)*. Maxwell's equations inside the microwave cavity including the food for constant permittivity and permeability and with no sources can be written as: *(Geedipalli et al., 2007)*.

$$\nabla \times E = -j\omega\mu H \tag{2}$$

$$\nabla \times H = j\omega\varepsilon_0\varepsilon^* E \tag{3}$$

$$\nabla . D = 0 \tag{4}$$

$$\nabla . B = 0 \tag{5}$$

The complex relative permittivity is defined as:

$$\varepsilon^* = \varepsilon' - j\varepsilon'' \tag{6}$$

Fourier's law with microwave term source is expressed as: *(Navarrete et al., 2012)*.

$$\rho C_P \frac{\partial T}{\partial t} = \nabla(k\nabla T) + P_V \tag{7}$$

The conversion of microwave energy to heat is defined by the following equation *(Vadivambal and Jayas, 2010)*.

$$P_V = \omega\varepsilon_0\varepsilon'' E^2 = 2\pi f \varepsilon_0\varepsilon'' E^2 \tag{8}$$

Fick's second law can be written as: *(Haghi and Amanifard, 2008)*.

$$\frac{\partial c}{\partial t} = D_e \nabla^2 c \tag{9}$$

Colour analysis

The colour analysis of the product was conducted by a Hunter Lab colorimeter to obtain some knowledge about the quality of the dried product. Three random readings for undried samples and each treatment (pulsing ratios 10, 4.5 and 2.5) were recorded. Three colour parameters, L*, a*, and b*, were used to study the colour changes. The L* refers to the lightness of the samples and ranges from black = 0 to white = 100. The negative value of a* indicates green, while the positive a* indicates red colours. The positive b* indicates yellow and the negative b* indicates blue colour *(Celen and Kahveci, 2013)*. Whiteness is an important characteristic of many food products as a colour quality. Deviation from whiteness may be perceived as yellowness. These parameters describe the perceptual change of the white and yellowish of colour of the product being processed *(Hirschler, 2012)*. In the food industry, the most frequently used whiteness index is expressed as Eq10: *(Judd and Wyszecki, 1963)*.

$$WI_{JUDD} = 100 - [(100 - L^*)^2 + (a^*)^2 + (b^*)^2]^{\frac{1}{2}} \tag{10}$$

Yellowness index is unduly neglected in the publications and it is reported in a few cases *(Hirschler, 2012)* which is defined by Eq.11*(Francis and Clydesdale, 1975)*.

$$YI_{FC} = 142.86\frac{b^*}{L^*} \tag{11}$$

The total colour difference was also calculated by following equation with respect to the undried product *(Celen and Kahveci, 2013)*.

$$\Delta E^* = \sqrt{(L^*_{undried} - L^*)^2 + (a^*_{undried} - a^*)^2 + (b^*_{undried} - b^*)^2} \tag{12}$$

One way analysis (ANOVA) was conducted to estimate the significant effect of pulsing ratio on the colour quality of the dried products. In addition Dunnett t-test method was applied to comparison of means.

Evaluation procedure

Before experimentation, samples in the closed container were taken out of the fridge to adapt to 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, 10, in three replications, where 1 sugar cube weighing 4.5 g was dried until sample moisture dropped to 0.06% (wet basis). Colour parameters of the dried product were measured and recorded to assess the quality of the dried product. Moreover, temperature distribution and moisture removal pattern of sugar cube were analyzed by spatial simulation contours in COMSOL. Furthermore the Moist sugar cube (3.23% w.b) properties needed for simulation of drying process in COMSOL are calculated from experimental values and listed in Table 2. Specific heat capacity and thermal conductivity were assumed as a function of moisture content of cube. Low moisture content of sugar cube is the main reason of why dielectric parameters can be assumed constant during the drying in spite of their moisture and temperature dependency *(Singh and Heldman, 2001)*.

Table 2

Dielectric and thermal properties of sugar cube

property	Value	Model
ε^* at 2.45 GHz	11.82 - 0.19 j	-
ρ (kg m^{-3})	1400	-
C_P (J kg^{-1}K^{-1})	-	1243.12797+(0.79835c)-(0.346451e-3c^2)
K (W m^{-1}K^{-1})	-	0.24861058013516+ (0.974352e-4c)-(0.422829e-7c^2)

RESULTS

Temperature distribution

Fig.1 presents the spatial distribution of temperature in the sugar cube. As observed, temperature distribution in microwave drying of cubes is intrinsically non-uniform due to the basic non-uniformity of electromagnetic radiation in a medium (Fig.2). However, the general pattern of temperature distribution is analogous in four contours (Fig.1-a, b, c, d).

As the first point, it is evident that the pattern of temperature variation is independent of pulsing ratio and simply the magnitude of temperature is changing. Furthermore, in pulsing ratio of 1.5 which means longer microwave radiation time, a bigger range of minimum-maximum temperature over the body (120˚C-170˚C respectively) resulted. Therefore, decreased pulsing ratio prolongs microwave radiation and thus temperature and non-uniform heating tend to increase.Technically speaking, in pulsed radiation method, when there is no radiation, variation of product temperature at the radiation period is balanced due to heat transfer, and because of reduced hot spots on the product, temperature differences are minimized. So, higher pulsing ratio gives more chance to conduct the heat over the body. This is in agreement with the findings of Yang and Gunasekaran (2004) *(Yang and Gunasekaran, 2004)*.

It is already accepted that better quality is obtained at uniform and low temperature dried products.

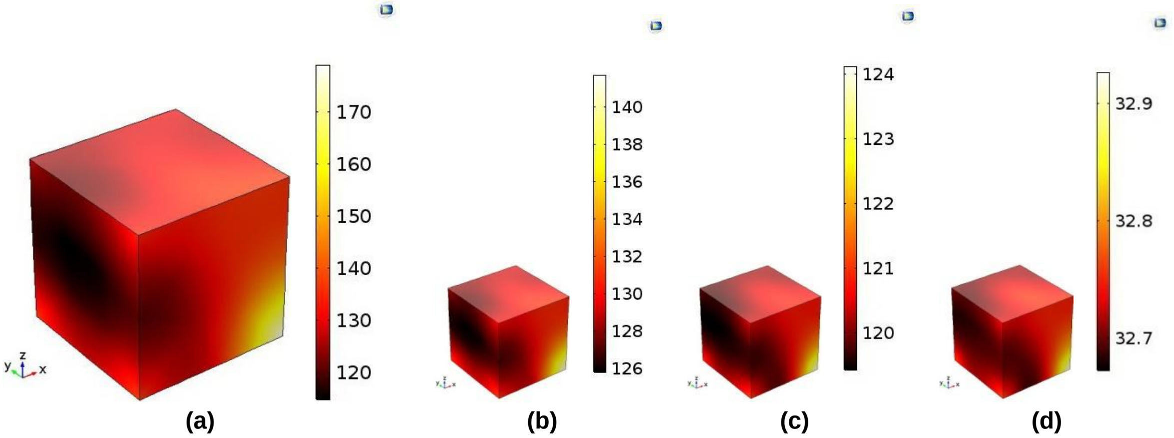


Fig. 1 - Temperature distribution (˚C) in sugar cube at the end of microwave drying process at different pulsing ratios: a) 1.5, b) 2.5, c) 4.5, d) 10

From Fig.1, it can be conferred that cube corners have the highest temperature values owing to reception of microwave radiation from three faces.

A proof of this claim is reported by Liu et al., 2013. Additionally, the corner exposed to the magnetron lamp benefits the highest temperature rise as it can be seen in Fig.1. This is consistent for moisture removal as shown in Fig.3.

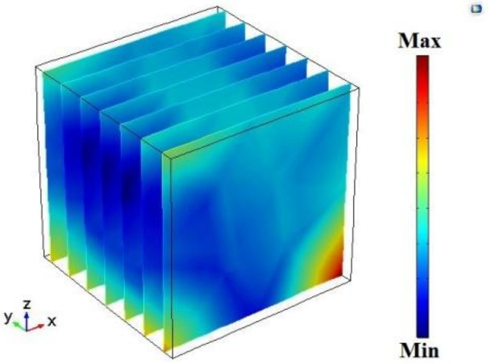


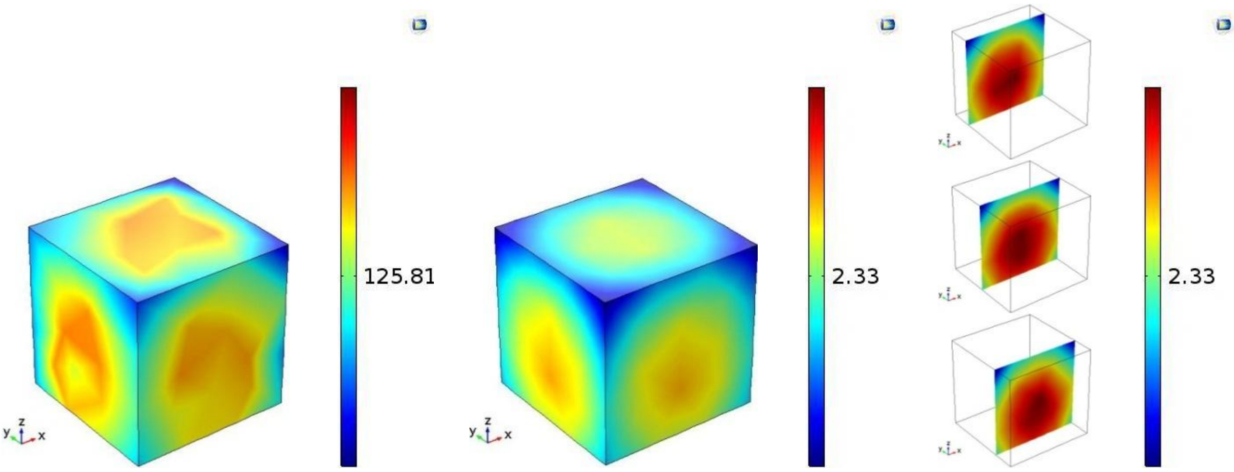
Fig. 2 - Electromagnetic field distribution (Vm-1) in sugar cube at 2.45 GHz frequency and 880 W microwave power

Moisture removal

An important issue to be noted here is that moisture, temperature and electromagnetic distribution patterns in the sugar cube are adaptable due to their strict interactions during the drying (Fig.1, 2, 3). While, as expected, the bottom face of sugar cubes had the highest values of moisture content due to cubes' positioning on the tray. Similar to temperature spatial variation, moisture variation pattern is also independent of pulsing ratios. Fig.3-a and Fig.3-b illustrate the moisture variation of sugars at the beginning and end of the process respectively. The moisture content has been reduced to the desired value, 2.33 molm^{-3}, which is quite comparable with experimentations.

Moisture concentration is further shown in three layers of the product at the end of the process (Fig.3-c). Contours shown in the figures reveal that as we move to the inner layers of the sugar, moisture concentration is higher. The reason is that, if one-dimensional analysis is considered and the incident microwave radiation is assumed to be normal to the surface of cube, the microwave power would be dissipated by the exponential decay of the incident power along that direction as a function of sample depth ($P = P_0 e^{-2\beta x}$) *(Yang and Gunasekaran, 2004)*.

Therefore, microwave power decreases with penetration within the product. This phenomenon is otherwise described; the low effective diffusivity of sugar cube can be stated as the main barrier to mass transfer from the centre zones of the product to outer layers keeping the distribution pattern as detailed in Fig.3-b, c.



(a) (b) (c)

Fig. 3 – Water concentration distribution (mol/m^3) in sugar cube at the a) first and b, c) end of microwave drying process

Colour analysis

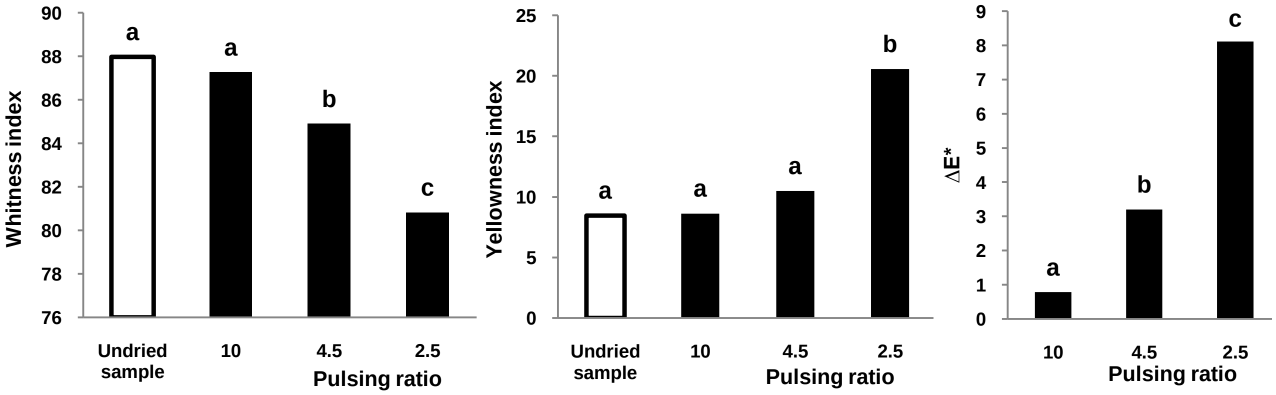
Table 3 details the average colour features of sugar cubes as indicators of quality during the drying process. Colour has a direct correlation with cosmetic appearance and consumer acceptability. In order to get a better perception of colour features, more commercial parameters have been plotted in Fig. 4.

The analysis of the colour quality can be made according to the similarity of the values of the dried product colour parameters to those of the undried one *(Celen and Kahveci, 2013)*. ANOVA analysis indicated that the effect of pulsing ratio on whiteness, yellowness and total colour difference is significant ($p < 0.001$).

Table 3

Average colour features for undried and dried sugar cubes using microwave at different pulsing ratios

Colour feature	**Undried sample**	**Pulsing ratio** **10**	**4.5**	2.5
L*	90.26	89.49	87.26	86.4
a*	-4.62	-4.76	-4.99	-5.31
b*	5.34	5.4	6.4	12.44



(a) (b) (c)

Fig. 4 - Whiteness, yellowness and total colour difference features for undried and dried sugar cubes using microwave at different pulsing ratios.

(Different letters state statistical significance at the 0.05 level using Dunnett t-test)

It is clearly demonstrated that higher pulsing ratio results in better whiteness, yellowness and total colour difference value which simply stated as white cube, less yellow final product and low colour difference to undried one (Fig.4). As inferred from Fig.1, higher radiation time, or lower pulsing ratio, leads to intense temperature rise and over burning of the cubes which means higher yellowness and worse appearance and marketability. The colour features of the dried sugar cube with pulsing ratio 10 are relatively much closer to those of the undried ones (Fig.4-c). Therefore, it can be inferred that the most preferable pulsing ratio (at 880 W microwave power) relative to colour quality is 10. In addition, yellow spots develop in the product due to burning at the pulsing ratio of 2.5 (Fig.4-b). Therefore, the pulsing ratio higher than 2.5 (at 880 W microwave power) has to be preferred to prevent the product burning and repulsive appearance.

CONCLUSIONS

An integrated electromagnetic-thermal-moisture concentration model has been developed for simulating the microwave drying of sugar cube at different pulsing ratios 1.5, 2.5, 4.5 and 10. The model has been solved with finite element method using COMSOL Multiphysics 5.2. Electromagnetic field, temperature and moisture distribution within sugar cube at the end of drying process were analyzed. Results presented in this study show the maximum absorbed microwave power, and then the highest temperatures and lowest moisture concentration at the corners of cube. Therefore, high interaction between electromagnetic field, temperature and moisture concentration was found in the microwave drying process. Moreover at the bottom corners, moisture concentration was more than top corners due to sugar cube positioning on the tray. Highest temperature heterogeneities occurred at lowest pulsing ratio 1.5. So, decreased microwave radiation reduces heating uniformity. Colour quality of dried sugar cubes was studied by measuring colour features L*, a* and b* and calculating whiteness, yellowness and total colour difference. Results revealed that higher radiation time, or lower pulsing ratio, leads to lower whiteness, higher yellowness, higher total colour difference and worse appearance and marketability. Thus, the preferable pulsing ratio based on colour indices and heating uniformity is 10.

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