SURFACE TEMPERATURE PROFILE, ENERGY-EXERGY ANALYSES AND THERMO-PHYSICAL PROPERTIES OF POTATO SLICES DRIED BY MICROWAVE AND MICROWAVE-CONVECTIVE DRYERS

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***Abstract*— In the present study, potato chips were dried at a microwave and hybrid (microwave + convective) dryer at PR 3 power rate. Effects of drying methods and conditions on surface temperature profile, drying characteristics, effective diffusion, activation energy, thin-layer drying model, specific moisture extraction rate (SMER), specific energy consumption (SEC), energy efficiency (EE), specific exergy loss (SEL), exergy efficiency (EXE), specific heat, thermal diffusivity, thermal conductivity and density were investigated. The lowest surface temperature (39.00 ºC) was observed in 160 W+55 ºC drying treatment and the greatest (128.30 ºC) in 160 W+75 ºC drying treatment. Among the thin-layer drying models, Wang-Sing model was determined as the best model. Effective diffusion values of drying treatments varied between $1.14x10^{-7}$- $3.18x10^{-10}$, activation energy values 79.12 kJ/mol (Microwave) and 126.96 kJ/mol (microwave + convective). SMER values 1006.57 - 1950.14 kg water/kWh, SEC values 8.86 - 14.31 MJ/kg water, EE values 2.55 - 19.39%, SEL values 0.42 - 12.68 kJ/kg varied between. Of thermophysical properties of potato chips, specific heat values varied between 837.69 - 848.13 J/kgºK, thermal conductivity values between 0.07 - 0.27 W/mºK, thermal diffusivity values between 1.163 - 3.774x10-6 m^2/s and density values between 700.60 - 839.41 kg/m^3.**

***Keywords*– Potato chips, temperature profile, energy analyses, thermophysical properties.**

I. INTRODUCTION

Improper harvest and storage of fruits and vegetables end up with about 10-30% losses. Such losses are quite high when the ever-increasing food demands of increasing populations (Sholberg and Conway, 2016; Yaşar *et al*., 2020). Drying offers a reliable mean of preservation post-harvest quality traits for fruits and vegetables.

Drying is among the oldest methods used for preservation of vegetables and fruits. Drying is technically defined as a process in which free moisture of a product is reduced to a certain storable water activity value (Anderson and Westerlund, 2014; Lamidi *et al*., 2019), microorganism activity is prevented (Batista *et al*., 2014; Macedo *et al.*, 2020) and a heat-mass transfer is realized. Various drying methods are applied in drying processes. Based on type of heat conduction, generally conventional and electromagnetic (radial) methods are preferred. As compared to electromagnetic driers, more homogeneous heat dissipation is encountered in drying processes made through conventional methods. Conventional methods are also more practical and easier to use. However, as compared to electromagnetic driers, conventional methods have some disadvantages in terms of drying durations, energy consumption and operational costs. Electromagnetic driers have more advantages over conventional ones in terms of drying ratio, drying duration, energy consumption and initial investment costs. Because of heat generation method, temperature control is not possible in drying process of electromagnetic driers. Such a case generates a non-uniform heat distribution throughout the drying process, thus, may negatively influences microstructure of the product (Morais *et al*., 2018; Yan *et al*., 2019; Boateng and Yang, 2020). There may occur tarnishes on protrusions and sharp points of dried materials. Microwave drier is an electromagnetic dryer. In microwave drying, drying conditions (temperature, duration, power, etc.) should be so controlled based on drying characteristics of the product (color, microstructure, etc.) as to minimize negative effects of microwave on final product. In this sense, temperature distribution within the material should be identified in microwave drying process.

Microwave dryers are commonly used in production of potato chips (Luo *et al*., 2019). Wang *et al*. (2010) subjected potato chips to osmotic pre-drying at 5, 10 and 15% salt solutions and 30, 40 and 50% sugar solutions, then to microwave-assisted freeze drying. It was observed that pre-treatments increased drying ratios and especially 5% sugar and 30% salt pre-treatments yielded better outcomes in terms of drying duration and quality traits of the final product. Supmoon and Noomhorm (2013) conducted drying experiments for potato chips at 5, 10 and 15 m/s air flow rates, 85 ºC constant air temperature, 0.16, 0.27 and 0.33 W/cm^2 electromagnetic wave intensity of jet air, jet air + infrared and convective drying methods. As compared to the other drying methods, jet air + infrared drying yielded greater drying ratio, less shrinkage, less firmness and color change. Barreto *et al.* (2019) investigated the effects of dipping and vacuum pre-treatments in microwave drying on reduction of free oil generated in potato chips. About 400 g potato sample was used and drying duration was identified as 60 minutes. Drying durations gradually decreased with increasing microwave powers from 200 W to 8000 W. Vacuum pre-treatment yielded yellower and crisper texture. However, the best quality traits were achieved with combined dipping + vacuum pre-treatments. Monteiro *et al*. (2020) dried potato chips in vacuum-assisted microwave dryer to produce potato chips and reported the lowest

moisture (0.028 g/g dry basis) and water activity (0.262) of the potato chips at drying duration of less than 30 minutes. It was indicated that vacuum-assisted microwave drying was a proper method for production of potato chips in terms of optical characteristics, microstructure and the other physical (size, volume, density, etc.) characteristics.

There is no information in literature about the temperature encountered on material surface in potato chips production in microwave and microwave-assisted hybrid driers. Such a case may then result in quality losses in potato chips temper (Vadivambal and Jayas, 2010; Barreto *et al*., 2019). Kaur *et al*. (2004) indicated that starch of different potato cultivars jellified at temperatures of 57.20 - 59.20 ºC and Anonymous (2010) indicated that potato stanches generally jellified at temperatures of between 59 – 68 ºC. Therefore, surface temperatures should be determined to control in drying processes.

In present study, effects of drying conditions of microwave and hybrid (microwave + convective) dryers on surface temperature profile of potato chips, effects of microwave powers on effective diffusion and activation energy values, effects of moisture change on thermophysical characteristics and effects of drying processes on energy and exergy values were investigated.

II. METHODS

A. Initial moisture of the material (%)

Fresh potatoes were purchased from a local market in Tokat, province of Turkey. Potatoes with similar color and freshness were tried to be selected. Initial moisture of the material was determined through drying at 70 ºC temperature until a constant change in material weight (Pixton and Warburton, 1973). Initial moisture content of potato chips was identified as 76.91%.

B. Drying processes

Before each drying experiment, potato chips were cut into 65x14x0.7 mm dimensions with the aid of a grater. For microwave drying processes, Vestel brand MD-GD23 model microwave oven was used. For hybrid drying process (microwave + convective), Hotpoin-Ariston brand MWHA 33343 model oven was used. Potato chips were dried under 360, 540, 720 and 900 W microwave power and 160 W+55 ºC, 160 W+65 ºC, 160 W+75 ºC, 350 W+55 ºC, 350 W+65 ºC and 350 W+75 ºC drying conditions. Drying processes were conducted at PR 3 rate (open for X time – closed for 2X time). Weight change of potato chips was monitored with the use of AND brand GF-3000 model precise balance (±0.01 g).

C. Monitoring temperature profile

To measure the temperature generated over the surface of potato chips under drying conditions applied in microwave and hybrid (microwave + convective) ovens, a noncontact infrared temperature sensor was installed over the microwave oven (Fig. 1).

Surface temperature measurements of potato chips were performed just before each drying weighing. The non-contact infrared temperature sensor was installed so as to see the potato chips placed over the rotary glass plate of the microwave oven. Temperature reading principles of the sensor is presented in Fig. 2.

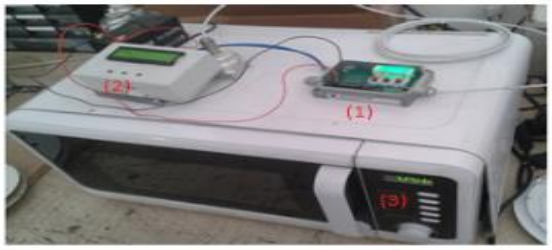


Figure 1. Installed infrared temperature sensor

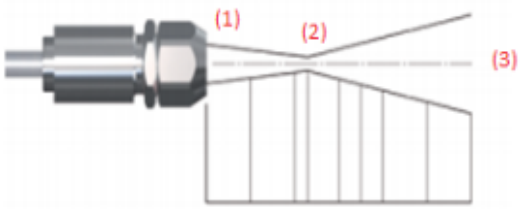


Figure 2. Reading principle of noncontact infrared temperature sensor (Optris, 2020)

According to Fig. 2, the reading range of the noncontact infrared temperature sensor installed on microwave oven is continuously contracted from the point it started to read surface temperature of the product (1) and then fans out (3) starting from the narrowest point (2) as to see the inside sections of the microwave oven.

Optris-brand CT LT-model non-contact infrared temperature sensor was used in present experiments. The sensor has a measurement range of between -50 ºC and 975 ºC. The sensor is accurately operated in the range of between -20 ºC and 180 ºC. The power requirement for the operation of noncontact infrared temperature sensor is 8-36 V DC. There is an input and output point of temperature sensor. Input point has the temperature reading head and the output point has the element from which the reading is transferred to computer environment. The noncontact infrared temperature sensor has 0/4-20 mA, 0-5 V, 0-10 V selectable analog values.

D. Initial moisture content

Total moisture content of potato chips (Ndb) was determined with the use of Eq. 1.

$$N_{db} = \frac{M_s - M_k}{M_k} \quad (1)$$

where, M_s = Initial weight, M_k = Final weight.

E. Thin-layer drying models

$$MR = \frac{M - M_e}{M_0 - M_e} \quad (2)$$

where: MR = Released moisture ratio, M = Instantaneous moisture of the product, M_e = Equilibrium moisture of the product, M_0 = Initial moisture of the product. Following Eqs. 3-7 were used to determine the best thin-layer drying model. The purpose of choosing these models is because they are used a lot in the literature.

$$MR = \exp(-kt) \text{ (Lewis, 1921)} \quad (3)$$

$$MR = k\exp(-ht + jt^{0.5} + m) \text{ (Jena and Das, 2007)} \quad (4)$$

$$MR = 1 + kt + ht^2 \text{ (Wang and Sing, 1978)} \quad (5)$$

$$MR = 1/(1 + ax) \quad (6)$$

$$MR = 1/(\mathrm{a} + bx) \quad (7)$$

where h, j, k, m are model coefficients, t is time.

F. Effective diffusion and activation energy

Equation 8 was used to calculate effective diffusion values (Corzo *et al*., 2008).

$$\ln MR = ln\frac{8}{\pi^2} - \frac{\pi^2 \cdot D_{eff}\, t}{4L^2} \quad (8)$$

where: D_{eff} = Effective diffusion (m^2/s), L = Half-thickness of the product (m). Equation 9 was used to calculate activation energy values (Corzo *et al*., 2008).

$$D_{eff} = D_o \exp\left(-\frac{E_a}{RT}\right) \quad (9)$$

where; D_o = Factor of the Arrhenius equation (m^2/s), R = Gas constant (8.3143 kJ/mol K), E_a = Activation energy (kJ/mol) and T (K) = Drying air temperature. Activation energy (E_a) value was calculated from the slope of the line drawn for natural logarithm of effective diffusion (D_{eff} coefficients vs $1/T$ values.

G. Specific moisture extraction rate (SMER)

Total energy values consumed by the driers until calculated final moisture of the potato chips were determined with the use of Polaxtor brand PLX-15366 model device. Specific moisture extraction rate was calculated as the ratio of moisture removed throughout the drying process to total energy supplied to the drier (Eq. 10) (Surendhar *et al*., 2019).

$$SMER = \frac{Moisture\ remowed\ during\ drying\ (kg)}{Total\ energy\ supplied\ to\ the\ dryer\ (kWh)} \quad (10)$$

where: $SMER$ = Specific moisture extraction rate (MJ/kg water).

H. Specific energy consumption (SEC)

The total energy required to dry a kilogram of potato chips was indicated as specific energy consumption. Equation 11 was used to calculate specific energy consumption (Surendhar *et al*., 2019).

$$SEC = \frac{p.t.10^{-6}}{m_w} \quad (11)$$

where: SEC = Specific energy consumption (MJ/kg water), p = Microwave power (W), m_w = Amount of moisture removed (kg), t = Drying duration (s).

I. Energy efficiency (EE)

Equation 12 was used to determine energy efficiency of the drying processes conducted in microwave and hybrid (microwave + convective) dryers (Surendhar *et al*., 2019).

$$n = \frac{m_w\, x\, \lambda_w}{p\, x\, t} \quad (12)$$

where: n = Drying efficiency of microwave and hybrid (microwave + convective) drying (%), m_w = Amount of moisture removed (kg), p = Microwave power (W), λ_w; Latent heat of evaporation (2257 kJ/kg), t = Drying duration (s) (Surendhar *et al*., 2019).

J. Specific exergy loss (SEL)

Equation 13 was used to calculate specific exergy loss encountered during the drying process of potato chips (Darvishi *et al*., 2014; Azadbakht *et al*., 2018).

$$ex = C_p\left((T - T_o) - T_o\, ln\left(\frac{T}{T_o}\right)\right) \quad (13)$$

where: ex: specific exergy loss (kJ/kg), C_p = Specific heat (kJ/kgK), T = Surface temperature of potato chips (K), T_o = Ambient temperature (K).

K. Exergy efficiency (EXE)

Equation 14 was used to determine exergy efficiency of microwave and hybrid drying processes (Darvishi, 2017).

$$ex = \frac{EX_{evap}}{p} \quad (14)$$

where: EX_{evap}= Exergy ratio used to remove moisture from the drying material (kJ/s), p = Microwave power (W). Exergy evaporation value should be determined to calculate exergy efficiency (Eq. 15) (Darvishi, 2017).

$$EX_{evap} = \left(1 - \frac{T_o}{T_p}\right).m_w.\lambda_{wp} \quad (15)$$

$$\frac{\lambda wp}{\lambda w} = (1 + 23\exp(-0.4X)) \quad (16)$$

where: EX_{evap} = Exergy ratio used to remove moisture from the drying material (kJ/s), m_w = Evaporated water ratio (kg/s), λ_{wp} = Latent heat of potato chips (J/kg), T_o = Ambient temperature (ºC), T_p = Surface temperature of drying material (ºC), X = Dry-based moisture content (kg water/kg dry matter).

L. Thermo-physical properties (TP)

Specific heat, thermal conductance, thermal diffusivity and density of potato chips were calculated as a function of dry-based moisture content. Equation 17 was used to calculate specific heat values (Huang *et al*., 2013).

$$C_p = 837 + 3348\left(\frac{X}{1+X}\right) \quad (17)$$

where: C_p= Specific heat (J/kgK), X = Dry-based moisture content (kg water/kg dry matter).

Equation 18 was used to calculate thermal conductivity of the potato chips (Ruiz-Lopez *et al*., 2004).

$$k = 0.49 - 0.44\exp(-0.206X) \quad (18)$$

where: k = Thermal conductivity (W/mK).

Equation 19 was used to calculate thermal diffusivity of potato chips (Ruiz-Lopez *et al*., 2004).

$$\propto = \frac{k}{Pp.C_p} \quad (19)$$

where; $\propto$ = Thermal diffusivity (m^2/s), Pp = Density (kg/m^3).

Density of potato chips was calculated with the use of Eq. 20 (Perusello *et al*., 2013; Tzempelikos *et al*., 2015).

$$P_p = 147.95\frac{X}{X_0} + 691.46 \quad (20)$$

where; P_p = Density (kg/m^3), X_0= Initial dry-based moisture content (kg water/kg dry matter).

III. RESULTS

A. Drying durations

Average drying durations of potato chips were determined for microwave and hybrid (microwave + convective) dryers. Samples were dried to a final moisture level of 0.82-0.38±0.03 (g moisture/g dry matter). Drying durations at 360, 540, 720 and 900 W power of microwave oven were respectively determined as 480, 240, 120 and 90 s. In hybrid dryer, drying durations at 160 W+55 ºC, 160 W+65 ºC, 160 W+75 ºC, 350 W+55 ºC, 350 W+65ºC

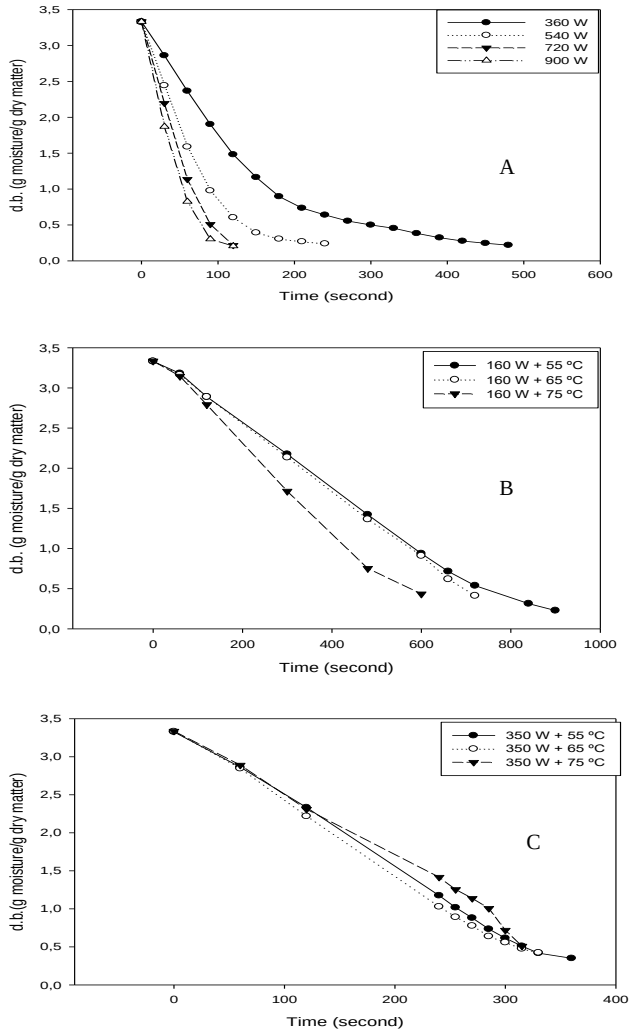


Figure 3. Drying durations of potato chips

and 350 W+75 ºC drying conditions were respectively determined as 900, 720, 600, 345, 330 and 315 s. Drying durations of potato chips are presented in Fig. 3.

Present findings revealed that microwave powers had significant effects on drying durations. About 41.67% decrease was observed with gradual increase in microwave powers. This situation is thought to be caused by the microwave power producing higher energy in the product. Drying durations were longer in hybrid dryer than in microwave dryer. In hybrid dryer, gradual increases in drying conditions resulted in limited differences in during durations. About 17.78% decrease was observed with gradual increase in microwave power and drying temperature values of hybrid dryer. Lechtańska *et al*. (2015) conducted microwave drying experiments in pepper and as compared to 180 W microwave power, reported 77, 84 and 85% decreases in drying durations at 540, 720 and 900 W power values, respectively.

B. Drying models

The moisture ratio removed from the potato chips during the drying processes were inputted into Lewis, Jena-Das, Wang-Sing, Rational-1 parameter-2 and Rational-2 parameter-1 models and the mathematical model with the best estimations was determined (Table 1).

According to Table 1, Wang-Sing model was identified as the best model in estimation of drying ratios at 900 W power of microwave dryer. The other models all yielded the best estimations at 360 W power of microwave dryer. Since all models were found to be significant at $P<0.05$, they could be used in estimation of drying ratios. The curves for the best and the worst model are presented in Fig. 4.

C. Effective diffusion and activation energy

Effective diffusion and activation energy values of potato chips dried in microwave and hybrid ovens are provided in Table 2. Effective diffusion values of potato chips dried in microwave oven dryer varied between 8.58×10^{-9}-3.67×10^{-8} m^2/s. Microwave powers significantly influenced effective diffusion values and increasing effective diffusion values were observed with increasing microwave powers.

Activation energy value of potato chips dried in microwave oven dryer was identified as 79.12 kJ/mol. In hybrid (microwave + convective) drying processes, effective diffusion values varied between 2.29×10^{-10} - 2.13×10^{-8} m^2/s and activation energy for (160 W+temperatures), (350 W+temperatures) of potato chips were identified as respectively 83.27 and 23.72 kJ/mol. In hybrid drying, microwave powers were more effective in effective diffusion values than hot air. Shorter drying du-

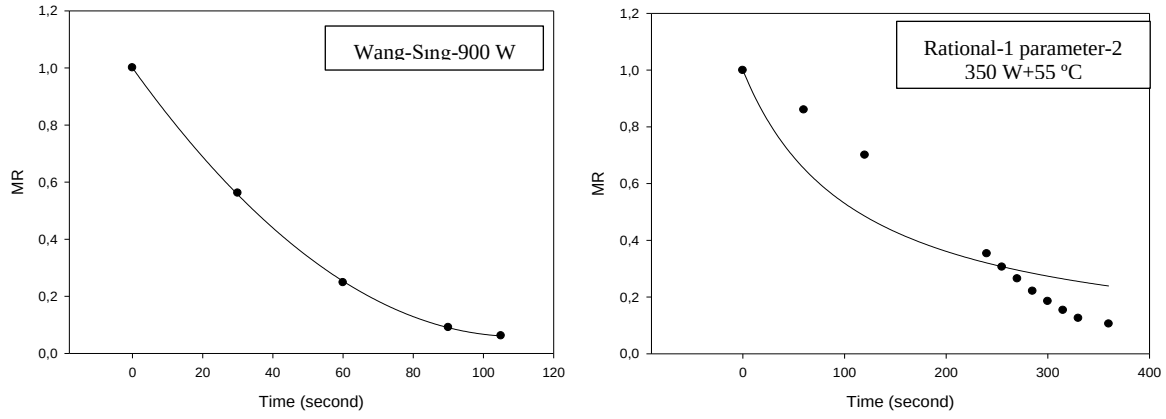


Figure 4. Drying curves for the best and the worst model

Table 1. Data for drying models

	Drying processes	a	b	h	j	k	m	R^2	P
Lewis	360 W					0.0065		0.9967	<0.0001
	540 W					0.0129		0.9963	<0.0001
	720 W					0.0181		0.9912	<0.0001
	900 W					0.0227		0.9955	<0.0001
	160 W+55 ºC					0.0021		0.9794	<0.0001
	160 W+65 ºC					0.0020		0.9773	<0.0001
	160 W+75 ºC					0.0026		0.9768	<0.0001
	350 W+55 ºC					0.0049		0.9731	<0.0001
	350 W+65 ºC					0.0051		0.9778	<0.0001
	350 W+75 ºC					0.0040		0.9843	<0.0001
Jena-Das	360 W			0.4072	0.8011	1.0123	0.0072	0.9939	<0.0001
	540 W			0.4105	0.7946	1.0150	0.0096	0.9936	<0.0001
	720 W			0.4132	0.7892	1.0173	0.0123	0.9842	<0.0001
	900 W			0.4154	0.7847	1.0114	0.0064	0.9916	<0.0001
	160 W+55 ºC			0.4050	0.8055	1.0409	0.0353	0.9698	<0.0001
	160 W+65 ºC			0.4050	0.8055	1.0363	0.0322	0.9663	<0.0001
	160 W+75 ºC			0.4053	0.8049	1.0384	0.0357	0.9687	<0.0001
	350 W+55 ºC			0.4065	0.8025	1.0411	0.0403	0.9571	<0.0001
	350 W+65 ºC			0.4066	0.8023	1.0391	0.0380	0.9657	<0.0001
	350 W+75 ºC			0.4060	0.8036	1.0267	0.0243	0.9751	<0.0001
Wang-Sing	360 W			0.0066		-0.0050		0.9814	<0.0001
	540 W			0.0025		-0.0098		0.9446	<0.0001
	720 W			0.0048		-0.0137		0.9983	<0.0001
	900 W			0.0077		-0.0171		0.9999	<0.0001
	160 W+55 ºC			0.0032		-0.0014		0.9951	<0.0001
	160 W+65 ºC			-0.0087		-0.0012		0.9992	<0.0001
	160 W+75 ºC			0.0028		-0.0017		0.9922	<0.0001
	350 W+55 ºC			0.0070		-0.0029		0.9946	<0.0001
	350 W+65 ºC			0.0097		-0.0031		0.9964	<0.0001
	350 W+75 ºC			0.0023		-0.0024		0.9990	<0.0001
Rational-1 parameter-2	360 W	0.0128						0.9308	<0.0001
	540 W	0.0253						0.9260	0.0004
	720 W	0.0330						0.9110	0.0223
	900 W	0.0462						0.9305	0.0222
	160 W+55 ºC	0.0036						0.8734	0.0011
	160 W+65 ºC	0.0032						0.8800	0.0025
	160 W+75 ºC	0.0038						0.8736	0.0158
	350 W+55 ºC	0.0089						0.8485	0.0003
	350 W+65 ºC	0.0093						0.8617	0.0005
	350 W+75 ºC	0.0064						0.9052	<0.0001
Rational-2 parameter-1	360 W	0.9167	0.0133					0.9389	<0.0001
	540 W	0.9548	0.0258					0.9288	<0.0001
	720 W	0.9727	0.0334					0.9124	0.0043
	900 W	0.9834	0.0465					0.9310	0.0034
	160 W+55 ºC	0.9000	0.0038					0.8896	<0.0001
	160 W+65 ºC	0.9120	0.0035					0.8966	<0.0001
	160 W+75 ºC	0.9136	0.0042					0.8921	0.0009
	350 W+55 ºC	0.9227	0.0092					0.8571	<0.0001
	350 W+65 ºC	0.9260	0.0096					0.8699	<0.0001
	350 W+75 ºC							0.9052	<0.0001

rations of microwave oven than the hybrid dryer was related to effective diffusion and activation energy values of the dryers. Xi *et al.* (2019) reported effective diffusion values of potato chips dried in ultrasound-supported infrared dryer as between 1.15×10^{-10} - 1.96×10^{-10} m^2/s. Dehghannya *et al*. (2019) dried potato chips at 360 W, 600 W and 900 W powers of microwave oven and reported effective diffusion values as 1.082×10^{-7}, 1.295×10^{-7} and 1.171×10^{-7} m^2/s, respectively.

D. SMER, SEC and EE values

Specific moisture extraction rate (SMER), specific energy consumption (SEC) and energy efficiency (EE) are provided in Table 3.

Drying methods significantly influenced SMER, SEC and EE values. In microwave drying, the greatest SMER values was observed at the lowest microwave power and the lowest SMER value was observed at the greatest microwave power.

Table 2. Effective diffusion and activation energy values of potato chips

Drying processes	Effective diffusion (m^2/s)	Activation energy (kJ/mol)
360 W	8.58×10^{-9}	79.12
540 W	1.77×10^{-8}	
720 W	3.44×10^{-8}	
900 W	3.67×10^{-8}	
160 W+55 ºC	2.29×10^{-10}	83.27
160 W+65 ºC	3.18×10^{-10}	
160 W+75 ºC	1.14×10^{-8}	
350 W+55 ºC	1.58×10^{-8}	23.72
350 W+65 ºC	1.59×10^{-8}	
350 W+75 ºC	2.13×10^{-8}	

Table 3. SMER, SEC and EE values

Drying processes	SMER (kg water/kWh)	SEC (MJ/kg water)	EE (%)
360 W	1950.14	14.31	8.42
540 W	1284.10	13.71	4.21
720 W	1182.77	9.21	3.27
900 W	1104.16	8.86	2.55
160 W+55 ºC	1418.22	13.82	16.33
160 W+65 ºC	1554.89	9.31	19.39
160 W+75 ºC	1037.78	10.64	14.14
350 W+55 ºC	1313.79	11.89	7.28
350 W+65 ºC	1230.40	11.41	7.25
350 W+75 ºC	1006.57	11.88	6.65

Despite the longer drying durations of low microwave powers, unit-time energy consumption was lower at low microwave powers. In hybrid drying, the greatest SMER value was observed at 160 W+65 ºC temperature. In microwave and hybrid drying processes, the greatest SEC value was observed at the lowest efficient drying conditions. Such a case was attributed greater energy consumptions or less moisture extraction rates. In terms of energy efficiency, hybrid drying was more efficient than microwave drying. In each drying process, energy efficiency values decreased with increasing drying conditions. In hybrid drying processes, energy efficiency decreased with increasing drying conditions, but only increased at 160 W+65 ºC drying conditions. Considering SMER and SEC values together, such a case was attributed less energy consumption as compared to the other drying processes. Dehghannya *et al.* (2018, 2019) reported decreasing specific energy consumptions of potato chips dried in microwave oven with increasing power values. Azimi-Nejadi and Salar Hoseini (2019) dried 3.5, 5, 7 and 9 mm thick potato chips at 200, 400, 600 and 800 W power values and reported specific energy consumptions as between 0.680 - 2.591 MJ/kg. Surendhar *et al*. (2018) dried ginger chips in microwave oven and reported energy efficiency values as between 9.24 - 24.75%. Ranjbaran and Zare (2013) dried soybean samples in microwave-assisted fluidized-bed dryer and reported energy efficiency values as between 9.41 - 13.98%.

E. SEL values

Specific exergy losses encountered during the drying processes of potato chips are presented in Fig. 5.

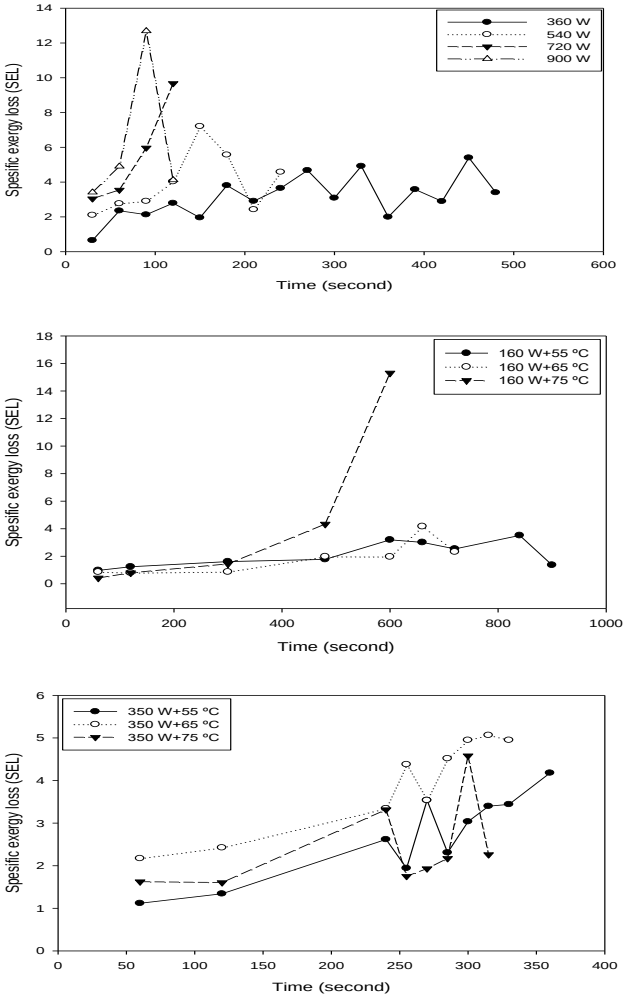


Figure 5. Specific exergy losses

In microwave drying, exergy loss values at different microwave powers varied between 0.65 - 12.68 kJ/kg. Increasing exergy loss values were observed with increasing microwave powers. In hybrid (microwave + convective) drying processes, exergy loss values were greater in 160 W + temperature combinations than in 350 W + temperature combinations. Exergy losses increased at low microwave powers. In hybrid oven, exergy losses varied between 0.42 - 15.30 kJ/kg at 160 W + temperature combinations and between 1.12 - 5.07 kJ/kg at 350 W + temperature combinations. In present study, to reduce exergy losses, low power values should be selected in microwave oven and high-power values should be selected in hybrid oven. Aghbashlo *et al.* (2009) reported exergy losses in drying processes of carrot chips as between 0.6677 - 14.1577 kJ/s. Beigi *et al.* (2017) reported average exergy loss in paddy drying processes as 3.63 kJ/s. Darvishi *et al.* (2016) reported exergy losses at 200, 300, 400 and 500 W powers of a microwave oven respectively as 8.23 - 14.39 MJ/kg, between 6.87 - 9.44 MJ/kg, 7.10 - 7.82 MJ/kg and 5.90 - 7.64 MJ/kg. Nikbakht *et al.* (2014) dried pomegranate seeds in a microwave-assisted convective dryer and reported decreased exergy losses at high microwave power levels.

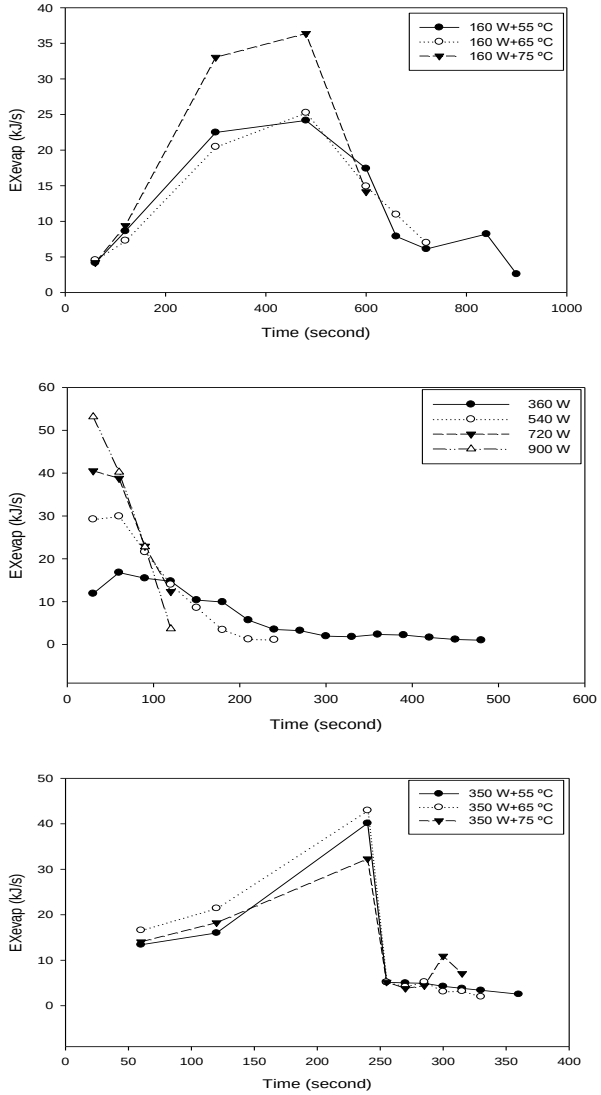


Figure 6. Exergy ratio used for evaporation

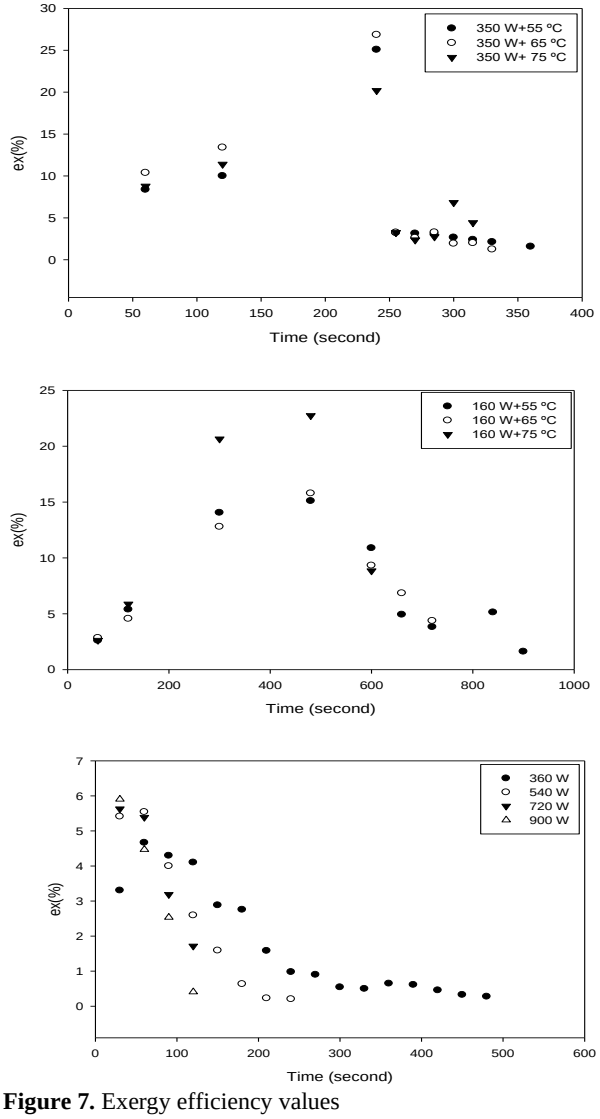


Figure 7. Exergy efficiency values

F. EXE values

Change in exergy ratios used for evaporation of moisture from the potato chips in microwave and hybrid drying methods is presented in Fig. 6.

Exergy efficiency values of potato chips in different drying processes are presented in Fig. 7.

Exergy ratios required to evaporate moisture increased with increasing microwave power and temperatures. However, remarkable decrease was observed in exergy evaporation values at 75 ºC drying temperature of hybrid drying. As can be seen in Fig. 6, exergy efficiency values were also significantly influenced by drying methods. Exergy efficiency values were lower in microwave oven than in hybrid oven. In hybrid oven drying processes, greater exergy efficiency values were observed in 160 W + temperature combinations. In microwave oven, mean exergy efficiency of drying processes at 360, 540, 720 and 900 W power values were respectively identified as 1.8020, 2.5269, 3.9811 and 3.3296%. In hybrid oven, exergy efficiency at 160 W and 55, 65, 75 ºC temperature combinations were respectively identified as 7.0584, 8.0779 and 12.1466%. Exergy efficiency values at 350 W and temperature combinations were respectively identified as 6.1653, 7.2199 and 7.5002%. Surendhar *et al*. (2019) dried ginger samples in microwave oven and reported increasing exergy efficiency values with increasing microwave powers. The exergy efficiency values at the lowest microwave power were reported as between 2 – 12%. Azadbakht *et al.* (2018) applied osmotic conditioning to orange chips for 30 minutes, then dried them at 90, 360 and 900 W microwave powers and reported exergy efficiency values as between 5 – 22%. High duration osmotic conditioning and high microwave powers increased exergy efficiency.

G. TP values

Specific heat, thermal conductivity, thermal diffusivity and density values of potato chips dried in microwave and hybrid (microwave + convective) ovens are provided in Table 4. Course of change in specific heat, thermal conductivity and density values are presented in Fig. 8.

Table 4. Thermophysical properties of potato chips

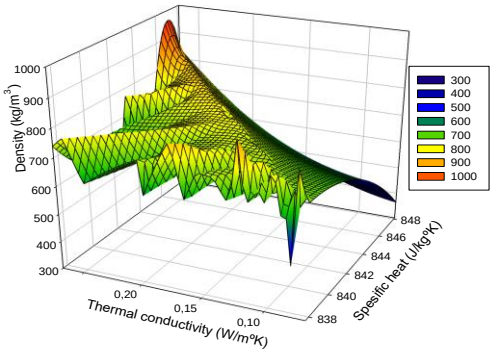
Thermophysical properties	Specific heat (J/kg^{o}K)	Thermal conductivity (W/m^{o}K)	Thermal diffusivity (m^2/s)	Density (kg/m^3)
360 W	Max. 848.12	0.27	3.772×10^{-6}	839.41
	Min. 837.73	0.07	1.181×10^{-6}	701.16
	Mean 840.60	0.13	2.064×10^{-6}	739.32
540 W	Max. 848.09	0.27	3.766×10^{-6}	839.41
	Min. 837.80	0.07	1.211×10^{-6}	702.14
	Mean 840.77	0.13	2.038×10^{-6}	741.64
720 W	Max. 848.13	0.27	3.773×10^{-6}	839.41
	Min. 837.73	0.07	1.181×10^{-6}	701.15
	Mean 841.94	0.16	2.390×10^{-6}	757.11
900 W	Max. 848.12	0.27	3.772×10^{-6}	839.41
	Min. 837.69	0.07	1.163×10^{-6}	700.60
	Mean 841.37	0.14	2.219×10^{-6}	749.52
160 W+55 ºC	Max. 848.11	0.27	3.770×10^{-6}	839.41
	Min. 837.76	0.07	1.194×10^{-6}	701.59
	Mean 842.25	0.16	2.471×10^{-6}	761.34
160 W+65 ºC	Max. 848.12	0.27	3.771×10^{-6}	839.41
	Min. 838.38	0.09	1.442×10^{-6}	709.77
	Mean 843.19	0.18	2.727×10^{-6}	773.75
160 W+75 ºC	Max. 848.13	0.27	3.773×10^{-6}	839.41
	Min. 838.45	0.09	1.471×10^{-6}	710.72
	Mean 843.77	0.19	2.850×10^{-6}	781.46
350 W+55 ºC	Max. 848.10	0.27	3.768×10^{-6}	839.41
	Min. 838.17	0.08	1.360×10^{-6}	707.02
	Mean 841.32	0.15	2.267×10^{-6}	748.96
350 W+65 ºC	Max. 848.12	0.27	3.772×10^{-6}	839.41
	Min. 838.42	0.09	1.458×10^{-6}	710.29
	Mean 841.41	0.15	2.288×10^{-6}	750.02
350 W+75 ºC	Max. 848.13	0.27	3.774×10^{-6}	839.41
	Min. 838.71	0.09	1.568×10^{-6}	714.08
	Mean 842.41	0.17	2.589×10^{-6}	763.29

Drying methods had significant effects on thermophysical properties of the potato chips. The greatest specific heat, thermal diffusivity and density values were observed in 720W power of microwave oven and 160 W+75 ºC drying conditions of hybrid oven. In microwave oven, thermophysical properties increased with increasing microwave powers, but decreased after 720 W. Therefore, 720 W was considered to be the critical power value in microwave drying. In hybrid oven, thermophysical properties were greater at 160 W power than the 350 W. In both microwave powers, thermophysical properties increased with increasing temperatures. Koç *et al.* (2008) dried quince chips with different drying methods and determined moisture-dependent change in density. Densities varied between 1050 - 1000 kg/m^3 in hot-air driying and between 950 - 400 kg/m^3 in freeze drying. Mariani *et al.* (2008) dried banana fruits at 17 - 65 ºC drying temperatures and reported dry-based moisture contents as between 3.43 - 0.01 and thermal diffusivity values as between $2.49\text{x}10^{-10}$ - $1.88\text{x}10^{-7}$ m^2/s. Yagua and Moreira (2011) dried potato chips at 120, 130 and 140 ºC temperatures of hot-air oven and reported densities of dried samples as between 1100 - 420 kg/m^3. Chakrabort *et al*. (2021) dried potato chips with foam-mat and the other methods and reported specific heat values of potato chips as between 3.9529 - 1.5579 kJ/kg^{o}C. Thermal conductivity values were significantly influenced by drying methods and values varied between 0.5626 - 0.2694 W/m^{o}C. Kumar *et al*. (2018) reported average thermal diffusivity value of potato chips as $0.89\pm0.01\text{x}10^{-6}$ m^2/s and average thermal conductivity value as 1.82±0.14 W/m^{o}K. Present findings on thermophysical properties comply with the results of previous studies.

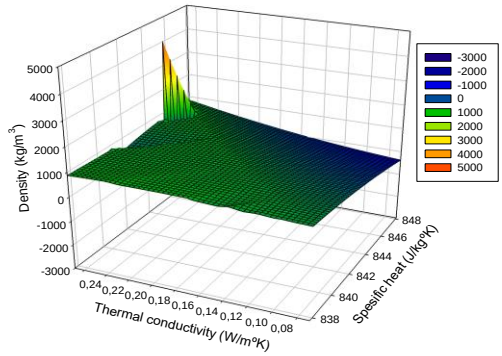
H. Surface temperature profile

Surface temperature profiles of potato chips dried in microwave and hybrid (microwave + convective) ovens are presented in Fig. 9.

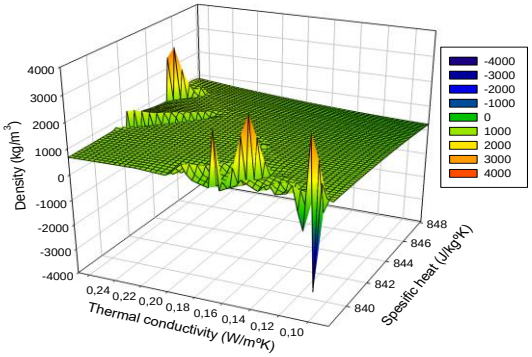
As can be seen in Fig. 9, time-dependent temperature distribution of potato chips dried in microwave and hybrid (microwave + convective) ovens rapidly increased at the beginning of drying processes. Moreover, this behavior is not observed for 160 W + 75 ºC and 350 W + 55 ºC. As can be seen in Fig. 9, time-dependent temperature distribution of potato chips dried in microwave and hybrid (microwave + convective) ovens rapidly increased at the beginning of drying processes, but then get stable with decreasing moisture levels. Temperature differences of dried potato chips encountered in drying processes are provided in Table 5. These temperature values are important in terms of the breakdown criteria of oils or other nutrients if microwave and microwave + oven devices will be used in the potato drying process.



a) Microwave drying

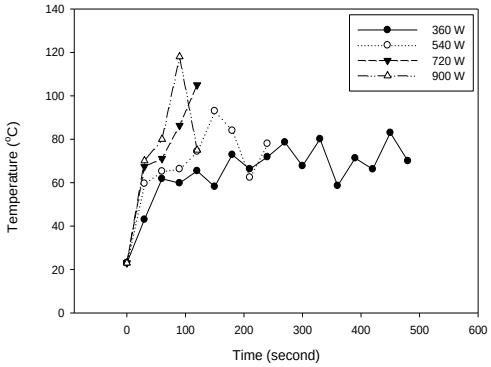


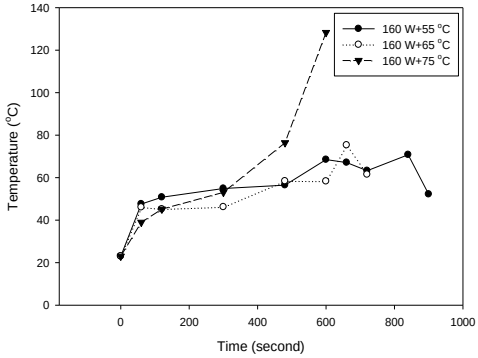
b) Hybrid (160 W+55, 65, 75 ºC)



c) Hybrid (160 W+55, 65, 75 ºC)

Figure 8. Distribution of specific heat, thermal conductivity and density values of drying methods.





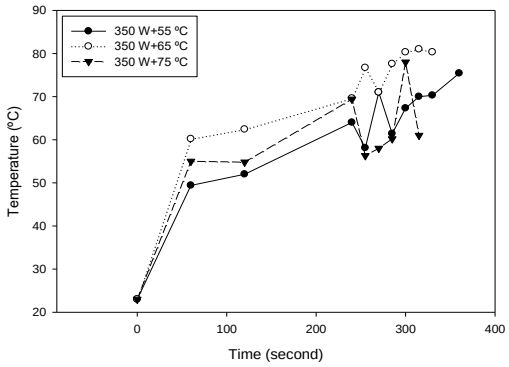


Figure 9. Surface temperature profiles throughout the drying processes

Table 5. Temperature and time differences

Drying conditions	Temperature difference at the end of the 1st minute	Drying time over 70 ºC temperature	Maximum temperature difference
360 W	38.80 ºC	180 s	60.00 ºC
540 W	42.20 ºC	120 s	70.00 ºC
720 W	48.10 ºC	90 s	82.00 ºC
900 W	57.00 ºC	120 s	95.00 ºC
160 W+55 ºC	24.60 ºC	120 s	47.80 ºC
160 W+65 ºC	23.10 ºC	60 s	52.30 ºC
160 W+75 ºC	16.00 ºC	300 s	105.30 ºC
350 W+55 ºC	26.40 ºC	60 s	52.40 ºC
350 W+65 ºC	37.20 ºC	90 s	58.00 ºC
350 W+75 ºC	32.00 ºC	15 s	55.00 ºC

* Ambient temperature was measured as 23±0.2 ºC.

As can be seen in Table 5, temperature differences at the end of the 1st minute and maximum temperature differences increased with increasing microwave powers. The greatest difference between the material temperature and ambient temperature at the end of the 1st minute was observed at 900 W microwave power. The greatest difference between ambient temperature and surface temperature was also observed at 900 W power. In hybrid oven, maximum temperature difference increased with increasing temperature only at 160 W + temperature combinations.

IV. CONCLUSION

In his study, energy, drying and thermophysical properties of potato chips dried in microwave and hybrid (microwave + convective) ovens were investigated. The lowest surface temperature (39.00 ºC) was observed in 160 W+55 ºC drying conditions and the greatest (128.30 ºC) in 160 W+75 ºC drying conditions. The best thin-layer drying model was identified as Wang-Sing model and the model yielded the best estimations at 900 W microwave power. Effective diffusion values varied between $1.14x10^{-7}$ - $3.18x10^{-10}$ and activation energy values varied between 79.12 kJ/mol (Microwave) and 126.96 kJ/mol (Hybrid). SMER values varied between 1006.57 - 1950.14 kg water/kWh, SEC values between 8.86 - 14.31 MJ/kg water, EE values between 2.55 - 19.39%, SEL values between 0.42 - 12.68 kJ/kg. In terms of thermophysical properties, specific heat values varied between 837.69 - 848.13 J/kgºK, thermal conductivity values between 0.07 - 0.27 W/mºK, thermal diffusivity values between 1.163 - 3.774×10^{-6} m^2/s and density values between 700.60 - 839.41 kg/m^3.

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