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Dehydration of infrared ginger slices: Heat and mass Transfer coefficient and modeling

Desidratação de fatias de gengibre por infravermelho: Coeficiente de transferência de calor e massa e modelagem

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ABSTRACT

Dehydration of plant products extends its shelf life and reduces its mass and volume, which increases transport and storage efficiency and adds value to food. However, it is an intensive process in energy and time, making necessary the search for more efficient technologies, Thus, this study aimed to investigate the infrared ginger dehydration process by approaching the constant period of dehydration to the theory of mass and heat transfer process to the wet bulb thermometer and the decreasing period of dehydration to liquid diffusion theory. We submitted 5.0 mm thickness and 2.0 cm diameter slices to a dryer with infrared radiation at 50, 60, 70, 80, 90 and 100 °C until constant mass. Heat and mass transfer coefficients, and effective diffusion coefficient increased linearly with temperature increasing, resulting in values ranging from 69.40 to 92.23 W m^{-2} $°C^{-1}$, 0.062 to 0.089 m s^{-1} and 3.81 x 10^{-9} to 1.13 x 10^{-8} m^2 s^{-1}. Variation of heat and mass transfer coefficients was described by a linear model and the variation of effective diffusion coefficient with the temperature was described with the Arrhenius relation, whose activation energy was 22.07 kJ mol^{-1}. The modified Henderson and Pabis model was able to satisfactorily describe the period of decreasing drying rate.

Index terms: Modified Henderson and Pabis; radiation; water content; *Zingiber officinale.*

RESUMO

A desidratação de produtos vegetais prolonga sua vida útil e reduz sua massa e volume, o que aumenta a eficiência de transporte e armazenamento e agrega valor aos alimentos. No entanto, é um processo intensivo em energia e tempo, tornando necessária a busca por tecnologias mais eficientes. Diante do exposto, objetivou-se investigar o processo de desidratação de gengibre por infravermelho através da aproximação do período constante de desidratação à teoria do processo de transferência de calor e de massa para o termômetro de bulbo molhado, e do período decrescente de desidratação à teoria de difusão liquida. Foram utilizadas fatias de 5,0 mm de espessura e 2,0 cm de diâmetro para serem secas em um secador com fonte de irradiação infravermelha nas temperaturas de 50, 60, 70, 80, 90 e 100 °C, até massa constante. Os coeficientes de transferência de calor e de massa, e o coeficiente de difusão efetivo, aumentaram linearmente com o aumento da temperatura, obtendo-se valores que variaram respectivamente de 69,40 a 92,23 W m^{-2} $°C^{-1}$, 0,062 a 0,089 m s^{-1} e 3,81 x 10^{-9} a 1,13 x 10^{-8} m^2 s^{-1}. A variação dos coeficientes de transferência de calor e de massa foi descrita por um modelo linear e a variação do coeficiente de difusão efetivo com a temperatura foi descrita por meio da relação de Arrhenius, cuja energia de ativação foi de 22,07 kJ mol^{-1}. O modelo de Henderson e Pabis modificado foi capaz de descrever satisfatoriamente o período de taxa de secagem decrescente.

Termos para indexação: Henderson e Pabis modificado; radiação; teor de água; *Zingiber officinale*.

INTRODUCTION

Ginger, obtained from the rhizomes of *Zingiber officinale*, is one of the most appreciated spices in the world, with attractive odor and spicy taste (Arablou; Aryaeian, 2017; Yu et al., 2017). In addition to using it as a spice, ginger is also a medicinal compound for having several pharmacological features, among which anti-inflammatory, antidiabetic, antioxidant, cardiovascular and anticancer activities (Gabr; Alghadir; Ghoniem, 2017; Pattnaik et al., 2016; Rahmani; Shabrmi; Alym, 2014).

Despite being found *in natura* (unprocessed), most ginger is marketed as post-concentrate and dry products (Jelled et al., 2015). Moisture content reduction

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of agricultural products inherent in the drying process relates to growth inhibition of microorganisms and prevention of biochemical modifications, causing many of the deterioration reactions to be avoided by humidity removal through the drying method (Deshmukh et al., 2014; Phoungchandang; Saentaweesuk, 2011; Pinela et al., 2011).

In addition, dehydration of plant products prolongs its shelf life and reduces mass and volume, which increases transport and storage efficiency and adds value to food (Baptestini et al., 2016), since these products, when they lose water, changes their organoleptic properties, such as aroma, texture, taste and color, increasing consumer interest (Dehghannya; Hosseinlar; Heshmati, 2018).

Drying of food is a very intensive process in energy and time, making it necessary to search for more efficient technologies (Ozdemir et al., 2017). Infrared dehydration offers many advantages over other drying methods (Adak; Heybeli; Ertekin, 2017), in which the radiation energy is transferred from the heating element to the product, heating the material faster and uniform without heating the circulating air (Ozdemir et al., 2017), reducing drying processes up to 50% (Nowak; Lewicki, 2004).

Drying of wet products is a complex process involving heating and mass transfer (Younis; Abdelkarim; El-Abdein, 2018). Moisture content can move inside a material submitted to drying by different mechanisms (Corrêa et al., 2012). In agricultural products, generally, porous hygroscopic, the possible transport mechanisms of moisture content are liquid diffusion, capillary diffusion, surface diffusion, vapor diffusion, thermal diffusion and hydrodynamic flow (Brooker; Bakker-Arkema; Hall, 1992).

In recent years, some studies have been conducted in the investigation of ginger drying behavior, using different methods and drying systems (Jayashree; Visvanthan, 2013; Afolabi; Tunde-Akintude; Oyelade, 2014; Parlak, 2015). Specifically for infrared radiation, An et al. (2016) evaluated the influence of this drying method on the chemical characteristics, antioxidant properties and microstructure of ginger slices. Kate and Sutar (2018) evaluated the use of this technology for the peeling of ginger rhizomes as a way to reduce water use and effluent disposal in this process. However, studies on the heat and mass transfer coefficients in infrared drying of ginger slices have not been reported.

This study aimed to determine heat transfer coefficient and process mass, to obtain and model the drying curves and to determine the diffusion coefficient and activation energy of infrared drying of ginger slices in the temperature range of 50 to 100 °C.

MATERIAL AND METHODS

This study took place at the Laboratory of Physical Properties and Quality Assessment belonging to the National Storage Training Center (CENTREINAR), located on the campus of the Federal University of Viçosa (UFV), Viçosa – Minas Gerais (MG).

Ginger roots (*Zingiber officinale*) from a farm in the municipality of Viçosa-MG were stored in BOD chambers at 20 ± 1 °C during the experiment. Ginger slices with mean initial moisture content of 5.548 $kg_a\ kg_{dm}^{-1}$ were cut with approximately 0.5 cm thick and 2.0 cm diameter. The measurements were made using a Mitutoyo digital pachymeter. Ginger slices were dried in infrared drying equipment (Figure 1 and 2), which provides the initial moisture content and water loss over the drying time. The uncertainties of the measurement instruments was calculated and shown in Table 1.

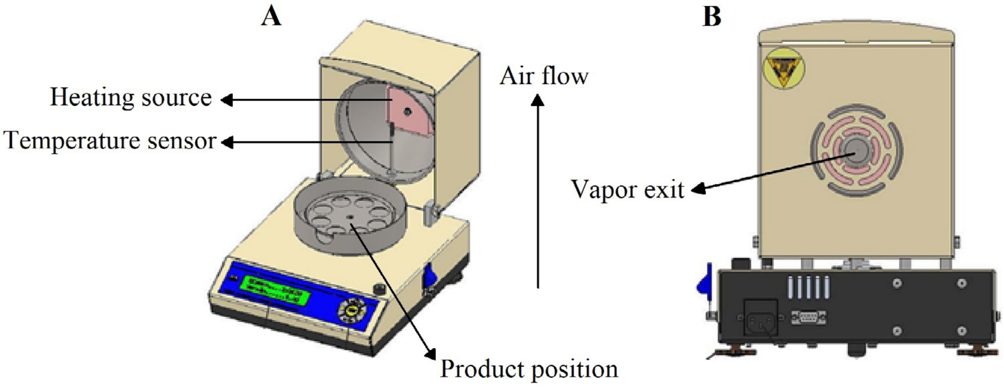

Figure 1: Schematic drawing of the infrared drying equipment, front view (A) and rear view (B) when drying chamber is open.
Source: Adapted from Gehaka (2011).

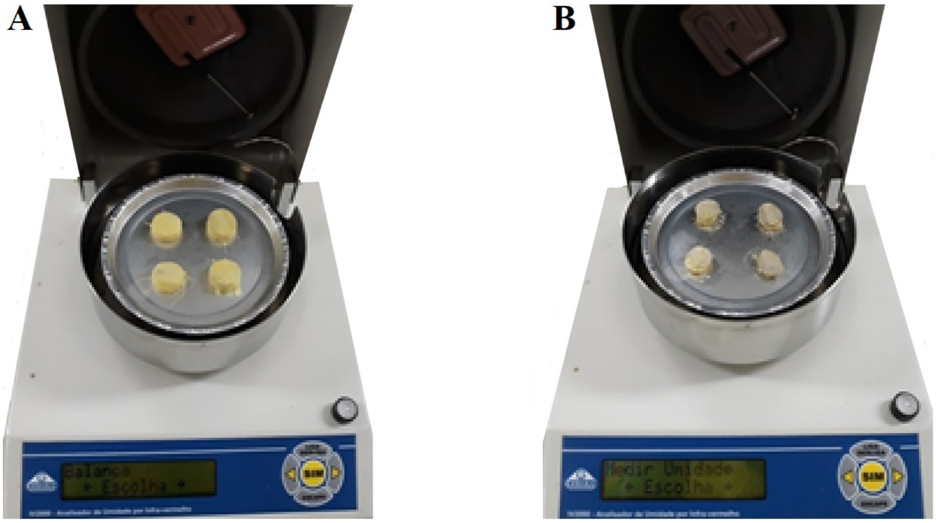

Figure 2: Ginger slices before (A) and after (B) of drying infrared process.

A drier with infrared radiation source (model IV 2500, Gehaka, São Paulo, Brazil) dried the ginger slices at 50, 60, 70, 80, 90 and 100 °C. This equipment contains 0.001 g precision scale and an automatic data acquisition system, which provides mass variation reading in 1 minute intervals. The equilibrium moisture content occurred when the variation of three consecutive readings was less than 0.01 g.

Table 1: Uncertainties of the measurement instruments used in the experiments.

Instruments	Uncertainty instrument (standard deviation)
Dryer model IV 2500 scale	0.423 g
Pachymeter	0.025 mm

Theories governing the study of constant drying period of agricultural products with high initial moisture contents may approximate to theories of heat and mass transfer balances for the wet bulb thermometer of a psychrometer. Thus, Equation 1 may represent the constant drying rate (Brooker; Bakker-Arkema; Hall, 1992).

$$\frac{dM}{dt}=\frac{h_c A}{h_{fg}}\left(T_\infty - T_{bu}\right)=\frac{h_m A}{R_V}\left(\frac{P_{vbu}}{T_{bu}}-\frac{P_{v\infty}}{T\infty}\right) \quad (1)$$

Where h_c - global coefficient of heat transfer (W m^{-2} $°C^{-1}$), h_m - global coefficient of mass transfer (m s^{-1}), h_{fg} - latent heat of vaporization (J kg^{-1}), R_v - universal constant for water vapor (0.462 J kg^{-1} K^{-1}), A - area (m^2), P_{vbu} - vapor pressure for wet bulb temperature (Pa), $P_{v\infty}$ - vapor pressure (Pa), T_{bu} - wet bulb temperature (°C), T_∞ - drying temperature (°C), dM/dt - constant drying rate, (kg s^{-1}).

From heat and mass transfer coefficients, we defined the Lewis number, which is relevant for any situation involving the simultaneous transfer of mass and heat by convection using the Equation 2 (Incropera; Dewitt, 2003):

$$\frac{h_c}{h_m}=\rho C_p L_e^{1-n}=\rho C_p\left(\frac{S_c}{P_r}\right)^{1-n} \quad (2)$$

Where ρ - specific air mass (kg m^{-3}), C_p - specific air heat (J kg^{-1} $°C^{-1}$), L_e - Lewis number (adm.), Sc - Schmidt number (adm.), Pr - Prandtl number (adm.).

This ratio can be used in both turbulent and laminar flow, and for most applications it is reasonable to assume a value of n = 1/3. In order to obtain specific air mass values for each drying air temperature and corrected for height, we used software GRAPSI®.

Table 2 shows the adjusted mathematical models traditionally used to describe the drying kinetics of agricultural products to the experimental data of ginger slices drying (in attachment).

Table 2: Mathematical models used for modeling ginger slice drying.

Model denomination	Model	
Diffusion approach	$\mathrm{MR=aexp(-kt)+(1\text{-}a)exp(-kbt)}$	(3)
Exponential of two terms	$\mathrm{MR=aexp(-kt)+(1\text{-}a)exp(-kat)}$	(4)
Henderson and Pabis modified	$\mathrm{MR=aexp(-kt)+bexp(-gt)+cexp(-ht)}$	(5)
Logarithm	$\mathrm{MR=aexp(-kt)+b}$	(6)
Newton	$\mathrm{MR=exp(-kt)}$	(7)
Page	$\mathrm{MR=exp(-kt^n)}$	(8)

t - drying time (min), k - drying constant ($\mathrm{min^{-1}}$), a, b, c, n - coefficients of the models (adm.).

Moisture ratio was determined in agreement to Equation 9. Simplification results from infrared drying in which the samples can dry to constant dry matter ($M_e = 0$) (Togrul, 2006). In addition, modeling occurred up to moisture content around 0.1364 $\mathrm{kg_a\ kg_{dm}^{-1}}$ in agreement to Resolution RDC No. 272 of September 22, 2005 from ANVISA (Brasil, 2005).

$$\mathrm{MR}=\frac{\mathrm{M_t\text{-}M_e}}{\mathrm{M_o\text{-}M_e}}\cong\frac{\mathrm{M_t}}{\mathrm{M_0}} \tag{9}$$

Where M_t - moisture content at t time ($\mathrm{kg_a\ kg_{ms}^{-1}}$), M_0 - initial moisture content ($\mathrm{kg_a\ kg_{ms}^{-1}}$), M_e - equilibrium moisture content ($\mathrm{kg_a\ kg_{ms}^{-1}}$).

The adjustment of the mathematical models occurred with non-linear regression with the Gauss-Newton method, using software Statistica 8.0® (Statsoft, 2004). When selecting the best model we considered: magnitude of coefficient of determination (R^2), relative mean error (MRE) (Equation 10), estimated standard deviation (SDE) (Equation 11), and the residual distribution.

$$\mathrm{MRE}=\frac{100}{n_{obs}}\sum_{i=1}^{n_{obs}}\frac{\left|Y_i-\widehat{Y}_i\right|}{Y_i} \tag{10}$$

$$\mathrm{SDE}=\sqrt{\frac{\sum_{i=1}^{n_{obs}}\left(Y_i-\widehat{Y}_i\right)}{GLR}} \tag{11}$$

Where Y_i - observed values, $_i$ - estimated values, n_{obs} - number of observed data, MRE - degree of freedom of the residue.

The effective diffusion coefficient was obtained by fitting the mathematical model of liquid diffusion to the experimental data, described by Equation 12. This equation is the analytical solution of Fick's second law, considering the geometric shape of the plate, conditions of moisture content of product surface, without considering the volumetric shrinkage of the product (Afzal; Abe, 1998; Baptestini et al., 2017).

$$\mathrm{MR}=\frac{8}{\pi^2}\sum_{i=1}^{n}\frac{1}{(2n+1)}\exp\left[-\frac{(2n+1)^2\pi^2 D_{ef}\,t}{4L^2}\right] \tag{12}$$

Where D_{ef} – effective diffusion coefficient ($\mathrm{m^2\ s^{-1}}$), n – number of terms in the equation (adm.), L – product thick (m).

The analytical solution of this equation is presented as an infinite series. Therefore, the finite number of terms (n) in truncation determines the accuracy of the results. This number was four (n = 4), since the effective diffusion coefficient did not change to higher values of (n).

Arrhenius' equation (Equation 13) was used to evaluate the temperature influence on effective diffusion coefficient (Doymaz; Tugrul; Pala, 2006; Gely; Giner, 2007; Gely; Santalla, 2007).

$$D_{ef}=D_0\ \exp\left(-\frac{E_a}{RT_{abs}}\right) \tag{13}$$

Where D_0 - pre-exponential factor ($\mathrm{m^2\ s^{-1}}$), E_a - activation energy ($\mathrm{kJ\ mol^{-1}}$), T_{abs} - absolute temperature (K).

RESULTS AND DISCUSSION

The drying curves of ginger slices (Figure 3) represent water loss of the product over drying time. The different drying periods are observed, constant rate period and decreasing rate, which according to Brooker, Bakker-Arkema and Hall (1992) occurs between moisture contents 2.33 to 3.00 $kg_a\ kg_{dm}^{-1}$. To determine the mass and heat transfer coefficient and the modeling, we considered the critical moisture content of 2.33 $kg_a\ kg_{dm}^{-1}$. According to Park et al. (2007), the amount of water available within the product in the constant rate period is very large. Water evaporates as free water, since its vapor pressure is constant and equal to the pure water vapor pressure at the temperature of the product. In turn, the temperature of the product is also constant and equal to the wet bulb temperature, because the mass and heat transfer transfers compensate.

Removing water inside the slices of ginger to the exposed surface is not sufficient to keep the product humidity. Thus, the period of decreasing drying rate conducted by the diffusion mechanism begins (Baptestini et al., 2015). In this period, according to Brooker, Bakker-Arkema and Hall (1992) heat transfer is not compensated by mass transfer because the internal resistance to water transport becomes greater than the external resistance. Thus, water migration decreases from inside the product to its surface, and the temperature of the product increases, reaching the air temperature drying.

The overall heat transfer coefficient (Figure 4A) and mass (Figure 4B) increased with increasing drying temperature, ranging from 69.40 to 92.23 W m^{-2} $°C^{-1}$ and 0.062 to 0.089 m s^{-1}, respectively. Values in this range were reported by Baptestini et al. (2017), Botelho et al. (2011) and Corrêa et al. (2009) working with infrared drying of banana slices, carrot slices and Fuji and Gala apple slices, respectively.

Bird, Stewart and Lightfoot (2004) state that the typical order of magnitude of heat transfer coefficient by convection is between 3.0 and 20.0 W m^{-2} $°C^{-1}$. The main reason for the higher values of such coefficient in this work is because drying is not only convective but a combination of radiation and convection (Corrêa et al., 2009). According to Incropera and Dewitt (2003) the coefficient depends on the condition of the limit layer, which is influenced by surface geometry, nature of fluid movement and various thermodynamic properties of fluid transport. Botelho et al. (2011) state that the coefficient of convective mass transfer defines the mass transfer rate without quantifying it, thus this coefficient is important to explain drying rates variation at different temperatures.

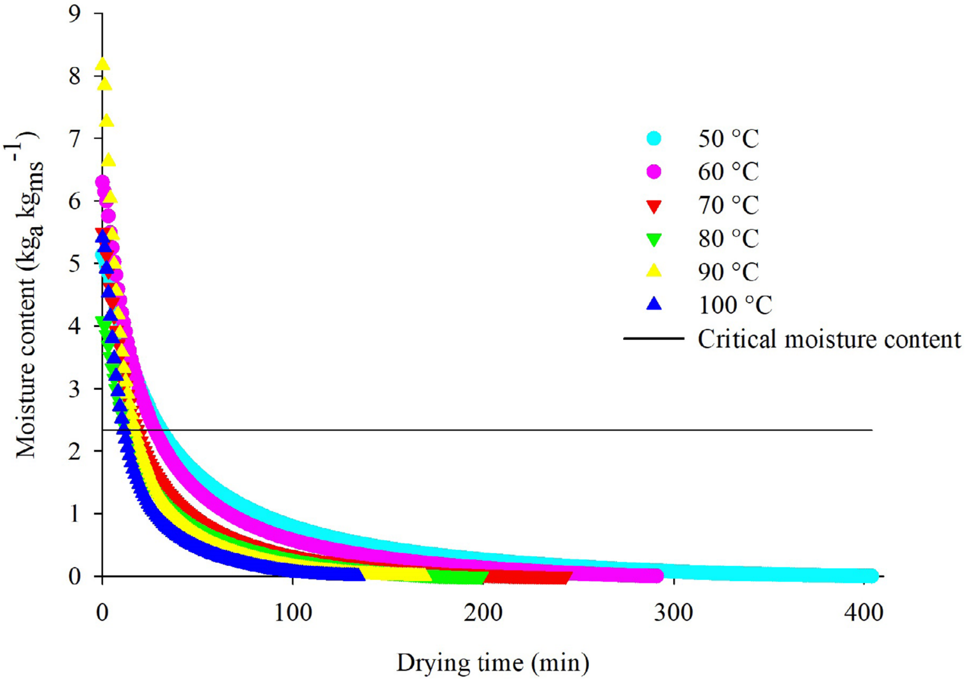

Figure 3: Ginger slice drying curves for 50, 60, 70, 80, 90 and 100 °C.

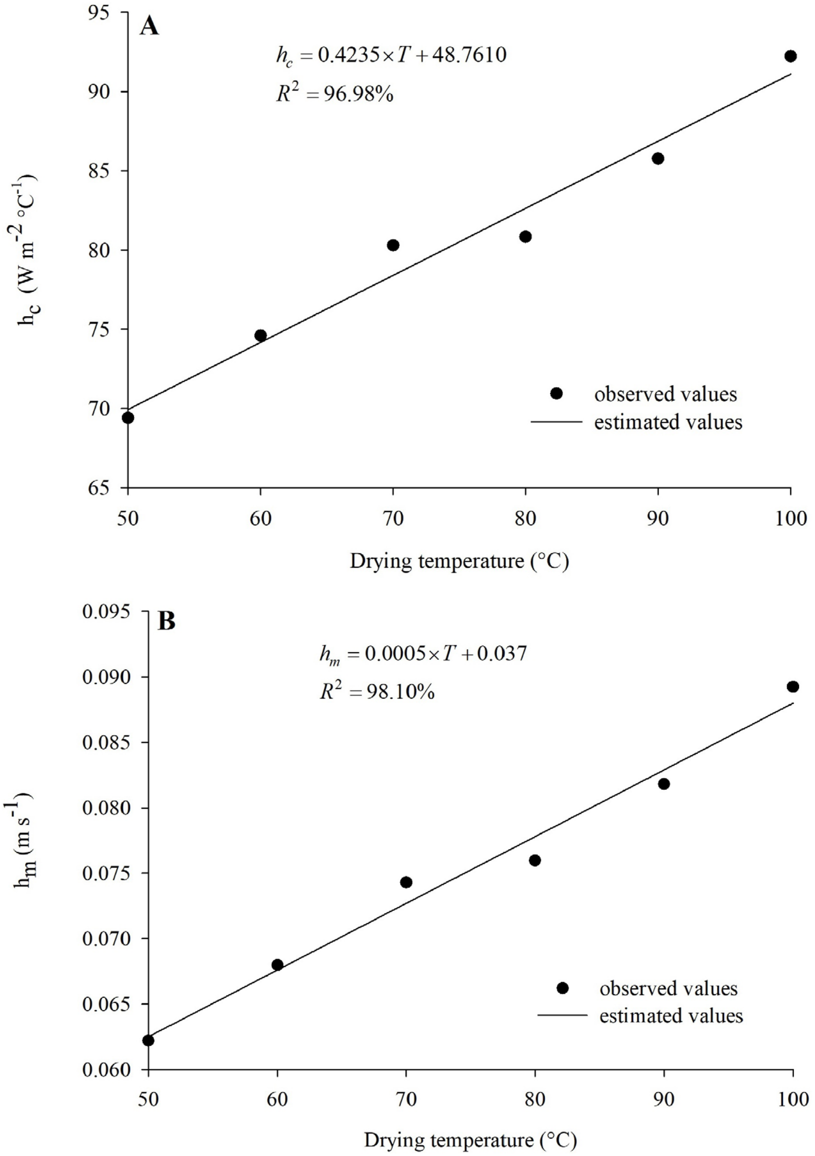

Figure 4: Global coefficient of transfer of heat (A) and mass (B) of ginger slices due to the drying temperature.

Lewis number (Le) values were 1.08; 1.10; 1.13; 1.15; 1.17 and 1.95 for the drying 50, 60, 70, 80, 90 and 100 °C. This is a dimensionless number defined as the ratio of thermal diffusivity to mass diffusivity. It makes it possible to have an indication of which mechanism dominates the process. According to Hatami and Ganji (2014), if Le >> 1, the process is limited by mass transfer; if Le << 1, the process is limited by heat transfer; and if Le = 1, the processes are coupled. Thus, both processes conduct infrared drying of ginger slices.

According to the specialized literature, for a model to be adequate to describe a phenomenon, it has to show a value less than 10% relative mean error (Mohapatra; Rao, 2005), reduced value of estimated standard deviation (Draper; Smith, 1998), high coefficient of determination (Kashaninejad et al., 2007) and random residual distribution (Corrêa et al., 2014; Goneli et al., 2011; Resende et al., 2011). Thus, by analyzing Table 3, only the modified Henderson and Pabis model meets all requirements simultaneously.

Table 3: Relative mean error (MRE), estimated standard deviation (SDE), coefficient of determination (R^2) and residual distribution (RD) for the mathematical models used in the modeling of ginger slice drying.

Model	50 °C				60 °C			
	MRE (%)	SDE	R^2 (%)	RD	MRE (%)	SDE	R^2 (%)	RD
(1)	0.675	0.004	99.97	B	0.866	0.005	99.95	B
(2)	22.311	0.019	99.20	B	28.983	0.022	99.20	B
(3)	1.104	0.001	99.99	R	1.549	0.002	99.99	R
(4)	16.957	0.018	99.33	B	21.983	0.019	99.19	B
(5)	40.183	0.039	96.76	B	46.771	0.039	96.53	B
(6)	9.602	0.014	99.57	B	13.223	0.016	99.42	B
	70 °C				80 °C			
(1)	1.979	0.006	99.93	B	3.066	0.008	99.88	B
(2)	25.095	0.020	99.13	B	16.594	0.019	99.33	B
(3)	0.729	0.001	99.99	R	1.018	0.001	99.99	R
(4)	19.114	0.018	99.35	B	14.760	0.018	99.41	B
(5)	42.853	0.038	96.99	B	33.433	0.038	97.22	B
(6)	13.729	0.018	99.35	B	9.615	0.018	99.38	B
	90 °C				100 °C			
(1)	2.990	0.009	99.84	B	5.047	0.012	99.75	B
(2)	35.363	0.022	98.91	B	21222	0.021	99.20	B
(3)	2.186	0.002	99.99	R	0.833	0.001	99.99	R
(4)	29.199	0.020	99.18	B	19.057	0.018	99.41	B
(5)	52.697	0.036	97.08	B	38.939	0.036	97.62	B
(6)	22.040	0.021	99.05	B	16.037	0.023	99.06	B

R: random; B: biased.

The curves of moisture dimensionless calculated and estimated by the Henderson and Pabis model, modified due to the drying time of ginger slices at different temperatures (Figure 5) confirm the good fit of the model. This satisfactorily explained all the drying. According to Oliveira et al. (2015) good correlation of the exponential part is expected, since the models mainly reflect this region of the graph. The error of the region tending to the equilibrium condition was minimized with the modeling up to 0.1364 $\text{kg}_a\ \text{kg}_{dm}^{-1}$ (Brasil, 2005).

Table 4 shows the Henderson and Pabis equations modified with the inclusion of constants obtained in the modeling.

The effective diffusion coefficient increased with increasing drying temperature (Table 5). Temperature increase interferes with the physical properties of the fluids, contributing to an increase in the effective diffusion coefficient. According to Corrêa et al. (2009) two of them are more important for agricultural products: viscosity and molecular vibration of water and air molecules. The first directly relates to water transport in the porous capillary. The second decreases the vapor pressure of air and increases the vapor pressure in the product, leading to an increase in water concentration gradient, facilitating water removal. Some studies on infrared drying show several values of effective diffusion coefficient (Baptestini et al., 2017; Botelho et al., 2011; Corrêa et al., 2009; Corrêa et al., 2012), which according to Doymaz (2008) is in the range from 10^{-11} to 10^{-9} $\text{m}^2\ \text{s}^{-1}$, as presented in this paper.

From Arrhenius representation (Figure 6), determining activation energy is possible. For ginger slices drying process, this was 22.07 kJ mol^{-1}. Zogzas, Maroulis and Marinoskouris (1996) reported that the activation energy generally ranges from 12.7 to 110.0 kJ mol^{-1} for food; this study showed consistent value.

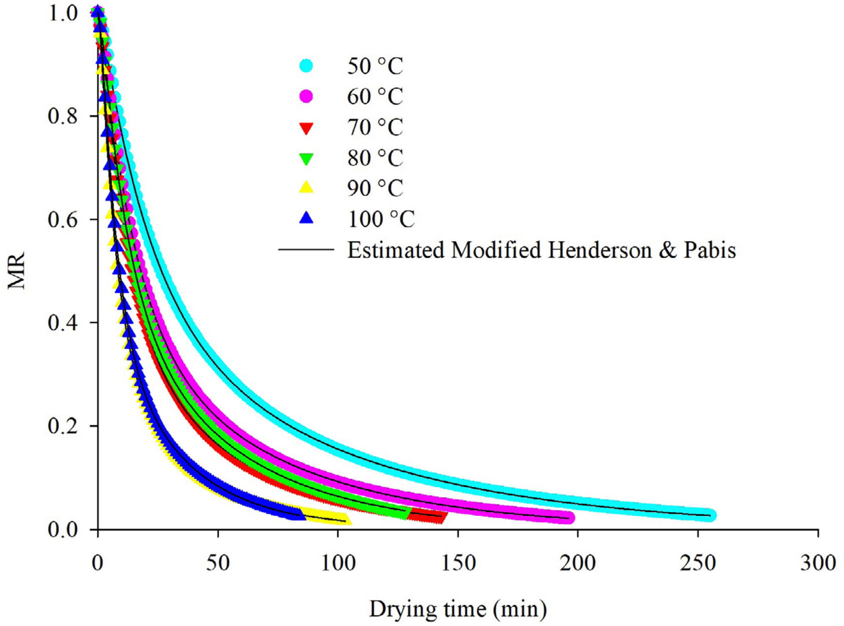

Figure 5: Moisture dimensionless calculated and estimated by the Henderson and Pabis model, modified due to the drying time.

Table 4: Henderson and Pabis model, modified to the experimental data of ginger slice drying.

Temperature (°C)	Henderson and Pabis modified
50	$\mathrm{MR}=0.572\exp(-0.049t)+0.463\exp(-0.011t)-0.037\exp(-0.913t)$
60	$\mathrm{MR}=0.627\exp(-0.070t)+0.420\exp(-0.015t)-0.048\exp(-1.049t)$
70	$\mathrm{MR}=0.651\exp(-0.088t)+0.415\exp(-0.020t)-0.068\exp(-0.820t)$
80	$\mathrm{MR}=0.601\exp(-0.092t)+0.487\exp(-0.020t)-0.088\exp(-0.727t)$
90	$\mathrm{MR}=0.365\exp(-0.030t)+0.739\exp(-0.146t)-0.104\exp(-1.251t)$
100	$\mathrm{MR}=0.438\exp(-0.033t)+0.737\exp(-0.157t)-0.174\exp(-0.746t)$

Table 5: Effective diffusion coefficient of ginger slices at 50, 60, 70, 80, 90 and 100 °C.

Temperature (°C)	Effective diffusion coefficient ($m^2\ s^{-1}$)
50	3.81×10^{-9}
60	5.62×10^{-9}
70	7.14×10^{-9}
80	6.54×10^{-9}
90	12.20×10^{-9}
100	11.30×10^{-9}

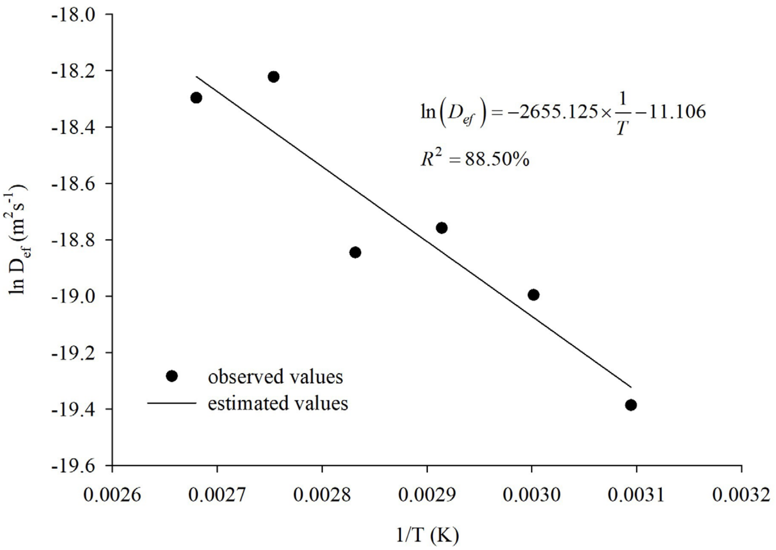

Figure 6: Arrhenius representation for effective diffusion coefficient of ginger slices at 50, 60, 70, 80, 90 and 100 °C.

CONCLUSIONS

The kinetics of infrared dehydration of ginger slices occurs simultaneously by heat transfer and mass transfer mechanisms. For the constant dehydration period, the heat and mass transfer coefficients varied respectively from 69.40 to 92.23 W m^{-2} $°C^{-1}$ and from 0.062 to 0.089 m s^{-1}. These coefficients variation with temperature was described by a linear model. For the decreasing dehydration period, the modified Henderson and Pabis model best described the kinetics of ginger slice drying, with effective diffusion coefficient ranging from 3.81 x 10^{-9} to 1.13 x 10^{-8} m^2 s^{-1} and activation energy of 22.07 kJ mol^{-1}.

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