Nexo Revista Científica

Vol. 36, No. 01 (Especial), pp. 53-65/Marzo 2023

ISSN-E 1995-9516
Universidad Nacional de Ingeniería

https://revistas.uni.edu.ni/index.php/Nexo
https://doi.org/10.5377/nexo.v36i01.15797

Experimental study of the kinetics and shrinkage of ginger in convective drying (*Zingiber officinale* Roscoe)†

Estudio experimental de la cinética y encogimiento del jengibre en secado convectivo (*Zingiber officinale* Roscoe)

Julio Rivas[1], Apolinar Picado[2], Joaquín Martínez[2], Rodolfo Espinosa[1*]

[1]Facultad de Ingeniería Química, Universidad Nacional de Ingeniería (UNI),
Avenida Universitaria, Managua 11127, Nicaragua
E-mail: rodolfo.espinoza@fiq.uni.edu.ni

[2]Department of Chemical Engineering, KTH Royal Institute of Technology
Teknikringen 42, SE-100 Stockholm, Sweden

(recibido/received: 31-mayo-2022; aceptado/accepted: 23-septiembre-2022)

ABSTRACT

In this work, the drying kinetics of ginger (*Zingiber officinale* Roscoe) was studied considering the shrinkage effect. The experimental data were obtained using three different temperatures (40, 60, and 80 °C). For the determination of shrinkage, two cutting orientations were employed. The volumetric and thickness shrinkage was evaluated by direct measurement. The shrinkage showed two periods during drying and had a considerable effect on the drying rate. An equation that relates the changes in the drying area as a function of the moisture content was determined. During drying, ginger showed only a falling rate period and exhibited a characteristic drying curve.

Keywords: *Zingiber officinale*; Drying; Shrinkage; Characteristic drying curve

RESUMEN

En este trabajo se estudió la cinética de secado del jengibre (*Zingiber officinale* Roscoe) considerando el efecto del encogimiento. Los datos experimentales se obtuvieron utilizando tres temperaturas diferentes (40, 60 y 80 °C). Para la determinación del encogimiento se emplearon dos orientaciones de corte. El encogimiento volumétrico y de espesor se evaluó por medición directa. El encogimiento mostró dos períodos durante el secado y tiene un efecto considerable en la velocidad de secado. Se determinó una ecuación que relaciona los cambios en el área de secado en función del contenido de humedad. Durante el secado, el jengibre mostró solo un período de velocidad decreciente y exhibió una curva de secado característica.

Palabra claves: *Zingiber officinale*; Secado; Encogimiento; Curva característica de secado

† In honour and loving memory of *Prof. em. Dr.-Ing. habil. Luis Moreno* (1942-2022).

* Author for correspondence

1. INTRODUCTION

Ginger (*Zingiber officinale* Roscoe) is a herbaceous perennial plant, which belongs to the Zingiberaceae family. Ginger is a rich source of active compounds (e.g., zingiberene, α-curcumene, gingerols, and shogaols). These compounds exhibit biological and pharmacological antioxidant, antilipidemic, antihyperglycemic, anti-inflammatory, antimicrobial, and anticancer properties. Ginger has been used as a spice and medicine for over 2000 years and more recently as a dietary supplement (Imtiyaz *et al*., 2013; da Silveira Vasconcelos *et al*., 2019).

Fresh gingers contain about 93% water and are perishable and sprouted during storage, which results in a decrease in the nutrients and storage quality (Ren *et al*., 2021). Drying is a process of removing water from foods and is characterised by simultaneous heat transfer and water movement. During the drying process, there is a loss of nutrients, and the sensory characteristics of the foods inevitably change, so it is necessary to select an appropriate drying method based on the different characteristics of the foods.

Many vegetables and fruits have been dried successfully including ginger. For instance, Thorat *et al*. (2012) reported an experimental study on thin-layer vacuum drying of ginger slices. Drying experiments were performed at a constant chamber pressure of 8 kPa and four different drying temperatures (40, 50, 60, and 65 °C). The results showed that increasing drying temperature accelerated the vacuum-drying process. All drying experiments had only a falling rate period, no constant rate period was observed. Under the evaluated experimental conditions, the two-term exponential model provided the best representation of the thin-layer drying characteristics of ginger slices.

Deshmukh *et al*. (2014) investigated the drying of ginger in a mixed-mode solar cabinet dryer. Freshly harvested ginger slices were successfully dried from initial moisture content of 621.50 to 12.19% (dry basis) and their drying characteristics, quality parameters, and kinetics were evaluated. Drying curves showed that drying occurred in the falling rate period and no constant period was observed. Page model was found to be most suitable to describe the drying kinetics of ginger in the solar dryer under natural convection among the tested models.

During the drying process, most of the foods simultaneously exhibit changes in volume and surface. This shrinkage phenomenon particularly affects the diffusion rate of the foods, which is one of the main parameters governing the drying process, thereby influencing the moisture removal rate (i.e., drying rate). In addition, shrinkage affects many properties of the foods. During drying, shrinkage occurs in all directions of the foods.

Ren *et al*. (2021) reported the combinative effect of cutting orientation and drying techniques on the physicochemical properties of ginger slices. Results showed that the longitudinal cut reduced the drying time significantly, by 15.12-29.6%, compared with the transverse cut and improved the physical properties of the dried ginger slices.

Buvaneswaran *et al*. (2022) studied the effect of drying temperature (40, 50, and 60 °C) and pretreatments conditions on shrinkage and rehydration kinetics of ginger slices. Results indicated that the pretreatments and drying temperature conditions significantly affect shrinkage-deformation, and a quadratic equation, as a function of moisture content, described the shrinkage behaviour of ginger slices. The process condition had a significant effect on the rehydration process. In all combinations, the rehydration ratio of ginger slices lies between 2.5 and 5.

Although several studies have been undertaken on the drying of ginger, however, information on the shrinkage effect appears to be scanty in the literature. The main objective of this study was to investigate the shrinkage effect on ginger during convective drying at different air temperatures.

2. MATERIALS AND METHODS

2.1 Material

Fresh ginger samples were procured from a local farmer in San Carlos, Nicaragua. After thorough cleaning and washing, the gingers free from injury were selected, manually peeled, and sliced.

2.2 Shrinkage

Among the methods in the literature to describe the shrinkage of foods, Gekas and Lamberg (1991) proposed to consider the shrinkage effect on moisture diffusion by incorporating volume changes into the effective diffusion coefficient, thus leading to:

$$\frac{D_{eff}}{D_{eff,0}} = \left(\frac{V}{V_0}\right)^{2/d} \tag{1}$$

where d takes value of one (1) in the case of a one-dimensional shrinkage, the value of three (3) in the case of an isotropic three-dimensional shrinkage, and d equal to a fractal in the most general case (Sjöholm and Gekas, 1995). Thus, d may be viewed as a measure of the degree of isotropicity of the deformation and is related to linear and volume shrinkage by:

$$S_v = S_t^d \tag{2}$$

where S_v and S_t are defined as:

$$S_v = \frac{V}{V_0} \tag{3}$$

$$S_t = \frac{L}{L_0} \tag{4}$$

where V and L are volume and thickness, respectively.

2.3 Shrinkage determination

Slices were produced by slicing both longitudinally and transversely the ginger samples to a thickness of 3 to 5 mm using an electric slicing machine. The ginger slices were soaked in water for two days to obtain a uniform moisture content. Subsequently, the ginger slices were cut into rectangles with a length of about 40 mm and a width of about 30 mm.

As suggested by Jarquín (1996), the edges of the rectangular ginger slices were coated with an oil-based layer (e.g., an enamel paint layer) before each experiment to obtain moisture removal only on both sides of the rectangular ginger slices.

Drying was performed in a convection oven with a temperature control of about ± 1 °C (e.g., a Fisher Scientific™ oven), which includes a metallic support structure as shown in Fig. 1. The metallic support structure includes hooks that were used as sample holders.

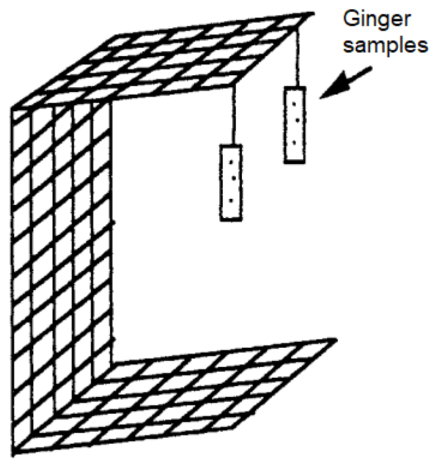

Fig. 1 Support structure for shrinkage experiments.

The shrinkage experiments were performed at air temperatures of 40, 60, and 80 °C. Before starting an experiment, the oven was run for at least half an hour to obtain steady-state conditions. In each experiment, a pair of longitudinal and transverse cut ginger samples were used, with similar size and moisture content. The ginger slices were hooked evenly in the metallic support structure and subsequently were put into the oven. The length, width, thickness, and mass of the ginger slices were recorded. The ginger slices were removed from the oven to conduct data sampling every half hour during the first two hours of the drying process because moisture evaporation was faster at the beginning. The subsequent data sampling was performed every hour until the mass was invariable. All the shrinkage experiments were performed in triplicate. Post-processing of these data yields an equation that relates the changes in the drying area as a function of the moisture content [$A_s = A_s(X)$].

2.4 Drying

A schematic arrangement of the experimental drying apparatus is shown in Fig. 2. The equipment may be divided into four main sections as follows: gas supply and dehumidification section, heating section, drying chamber, and analysing equipment. The blower (B) supplies a gas flow--a broad range of flow rates is possible by changing the rpm setting through the frequency inverter (FI). The air passes through an adsorption column (AC) containing a dehumidificant (silica gel) to obtain a process air of low humidity content (less than 1.0% relative humidity) measured by a hygrometer. The air velocity is measured by an anemometer. After dehumidification, the air is pre-heated with electrical resistance (ER) heaters of up to 2 kW each. Temperature is controlled by means of a temperature controller (TC) that supplies heat by means of an electrical resistance heater as its final control element. Before entering the drying chamber, a static mixer homogenises the temperature by mixing the gas. The sample is put in the sample holder (SH) inside the drying chamber and is supported on a weighing balance (WB) through an oil-sealed shaft. The cross-sectional area and depth of the sample holder are 30.65 mm × 109.8 mm and 3 mm, respectively. The drying chamber has a uniform cross-sectional area of 90 mm × 110 mm. The sample's weight history is recorded on a computer (C). It is possible to take a reading every 12 seconds (Mendieta *et al*., 2015).

The drying experiments were performed at air temperatures of 40, 60, and 80 °C and a velocity of 1 m/s. Before starting an experiment, the drying apparatus was run for at least half an hour to obtain steady-state conditions. For the drying experiments, transverse cut ginger samples were used. The sample was loaded evenly within the sample holder, which covered the whole drying area. The sample holder was put into the tunnel dryer. The drying time and mass of the sample were recorded. The experiment was stopped until the mass was invariable.

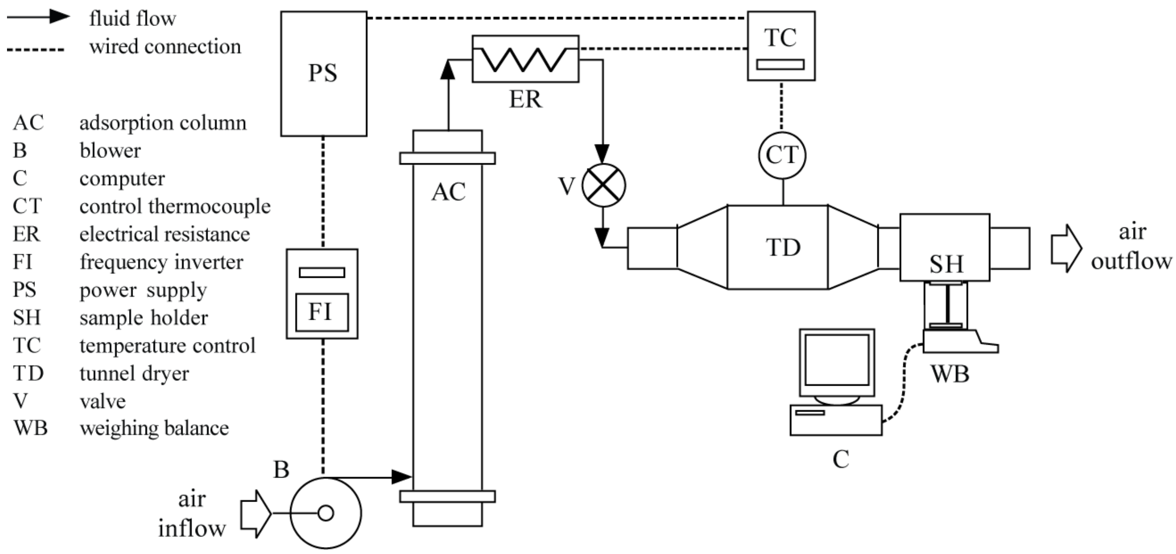

Fig. 2 A schematic diagram of a tunnel drying system.

After drying by the apparatus above, the sample was further dried in an oven at 60 °C for 18 hours to determine its oven-dry mass (m_s). The initial mass, drying mass and oven-dry mass were determined with a precise analytical balance. All the drying experiments were performed in triplicate. Post-processing of these data yields drying kinetics.

2.5 Drying kinetics

The moisture content is computed as follows:

$$X_i = X_{i-1} + \frac{1}{m_s}\left(\frac{m_i - m_{i-1}}{t_i - t_{i-1}}\right) \tag{5}$$

where X is the moisture content at any time (dry basis), m is the mass of the sample at any time, and t is the time. The drying rate is defined as:

$$N_v = -\frac{m_s}{A_s}\frac{dX}{dt} \tag{6}$$

where N_v is the drying rate at any time and A_s is the drying area. Using the moisture content data as a function of time and a centred approximation of the derivative, it is possible to determine the drying rate as follows (Picado *et al.*, 2006):

$$N_v\left(X_i\right) = -\frac{m_s}{A_s\left(X_i\right)}\left(\frac{X_{i+1} - X_{i-1}}{t_{i+1} - t_{i-1}}\right) \tag{7}$$

The processing of the experimental data is performed using a program written in MATLAB®, this program reads the experimental data obtained and plots the drying curves and drying rate curves according to Eqs. (5) and (7).

The characteristic drying curve (CDC) concept, firstly introduced by van Meel (1958), relies on an appropriate transformation of the drying rate curve coordinates to look for a single normalised drying rate curve, which does not depend on external parameters (e.g., air conditions). The variable transformations proposed by van Meel (1958) are:

$$\phi = \frac{X - X_{eq}}{X_{cr} - X_{eq}} \tag{8}$$

and

$$f = \frac{N_v}{N_w} \tag{9}$$

where ϕ is the characteristic moisture content, f is the relative drying rate, X_{eq} is the equilibrium moisture content, X_{cr} is the critical moisture content, and N_w is the drying rate at the constant rate period. The general form of the CDC is given by $f = f(\phi)$.

By plotting f vs. ϕ at the different temperatures tested, a group of curves is obtained whose behaviour, if common, describes a characteristic drying curve to which a mathematical function (e.g., a polynomial function) can be determined. It is assumed that a unique relationship between f and ϕ can be found for a specific material.

3. RESULTS AND DISCUSSION

3.1 Shrinkage characteristics

Figure 3 presents how volumetric shrinkage (S_v) depends on the moisture content (wet basis) of the ginger samples at 60 °C. In a convective drying process, shrinkage normally occurs due to cellular collapse because of the cell wall and membrane damage by heating. As can be seen from Fig. 3, the shrinkage showed two periods during drying. The first period corresponded to a falling period in which the shrinkage of the ginger slices is higher due to high mass transfer. The second period corresponded to a period in which the shrinkage was essentially constant due to the internal resistance to moisture migration and low free moisture. This could also be due to the transition from a rubbery to a glassy state and case hardening (Lin *et al*., 2020). This shrinkage behaviour is similar for all the temperatures (40, 60, and 80 °C) and longitudinal and transverse cut samples.

It was observed that the shrinkage of the transverse cut samples was higher than the shrinkage of the longitudinal cut samples. This could be due to the cutting orientation of the internal fibres of the ginger samples that left empty spaces within the ginger slices and between the fibres, thus causing the drying air to penetrate and produce higher moisture evaporation. In addition, the shrinkage was progressive towards the centre, thus making the ginger slices take a concave shape. The results of Fig. 3 suggest that the volume shrinkage of the ginger slices equals the volume of removed water.

Analysing the relationship between the volume change (S_v) and the thickness change (S_t) experimentally obtained, exponent d in Eq. (2) was calculated by linear regression of ln(S_v) vs. ln (S_t). A typical plot of such results is shown in Figs. 4 and 5. Longitudinal cut samples showed a d-value of 1.55. A fairly good fit was obtained (see Fig. 4) as represented by a correlation coefficient of 0.983 (for all temperatures). The degree of shrinkage of the transverse cut samples is shown in Fig. 5. The d-value is 1.65 with a correlation coefficient of 0.989 (for all temperatures). As is shown, the exponent d slightly changed with the drying temperature and cutting orientation. The results suggested an anisotropic behaviour (related to the change of ginger structure during drying). Further, the results confirmed the general assumption of one-dimensional moisture transport.

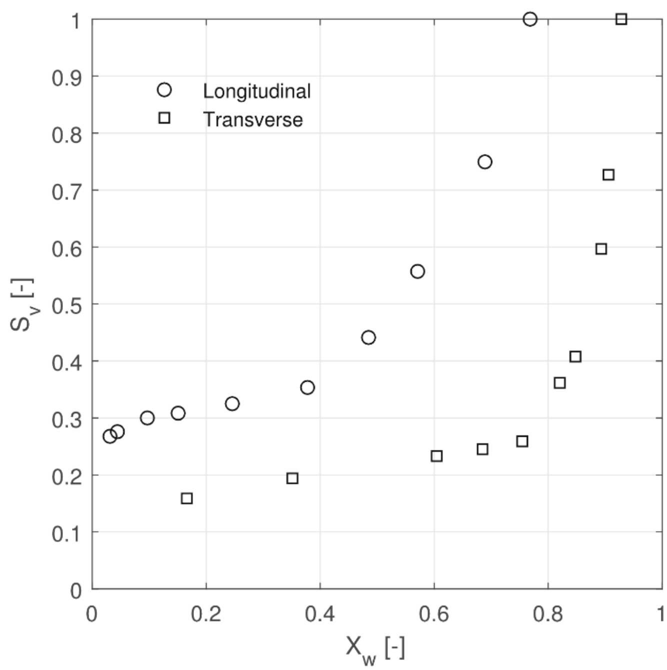

Fig. 3 Volumetric shrinkage vs. moisture content (wet basis) at 60 °C. Comparison between longitudinal and transverse cuts.

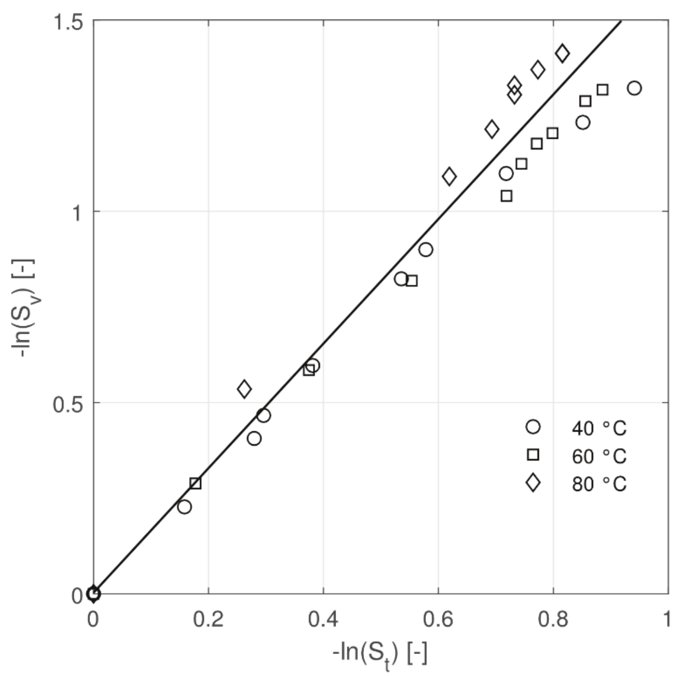

Fig. 4 Relationship between S_t and S_v (longitudinal cut samples).

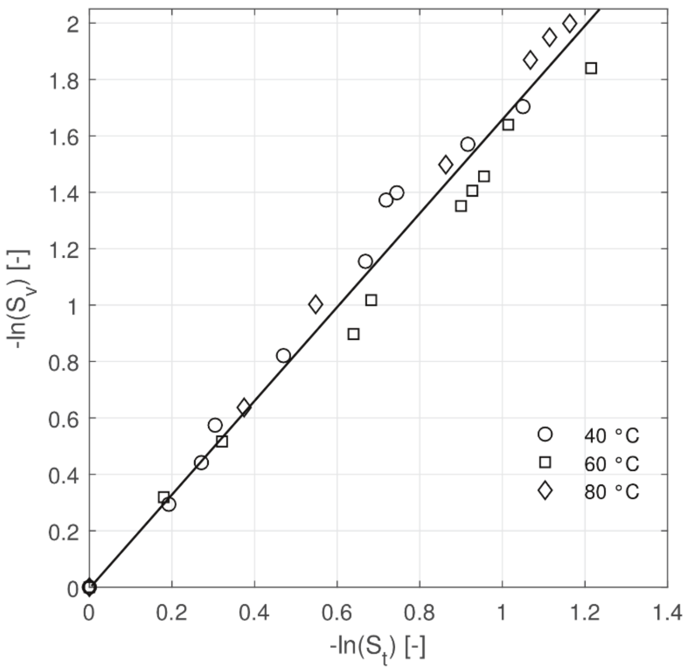

Fig. 5 Relationship between S_t and S_v (transverse cut samples).

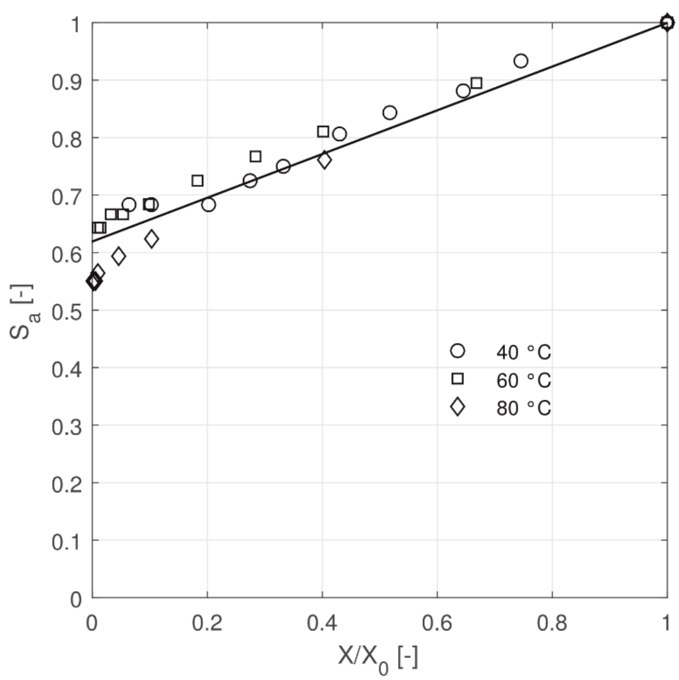

Fig. 6 Relationship between S_a and moisture content ratio (longitudinal cut samples).

The area shrinkage factor, S_a, showed a linear correlation with the moisture content ratio (X/X_0), given in Figs. 6 and 7, irrespective of the cutting orientation. A good linear regression is obtained by fitting all the experimental data. The regression analysis was performed using MATLAB®'s Curve Fitting Tool. The regression analysis facilitates the determination of an equation that relates the changes in the drying area as a function of the moisture content (dry basis).

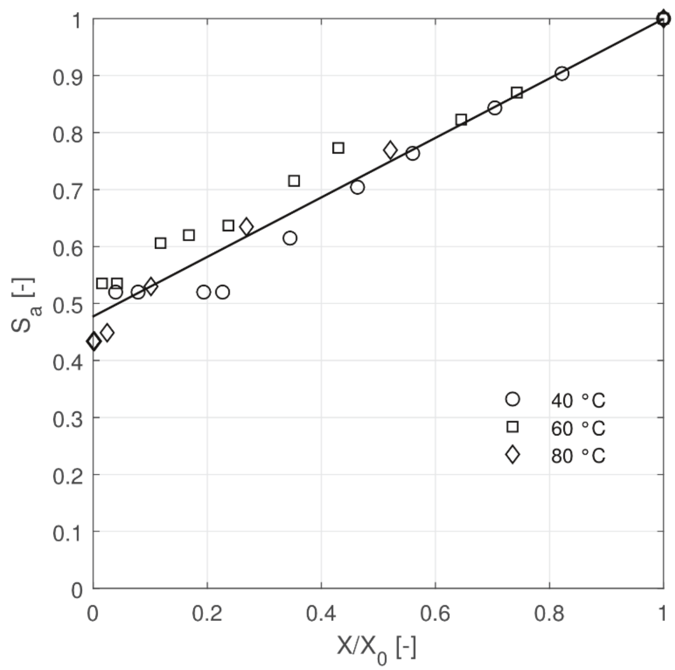

Fig. 7 Relationship between S_a and moisture content ratio (transverse cut samples).

For longitudinal and transverse cut samples, the equation that relates the changes in the drying area as a function of moisture content is:

$$A_s(X) = 0.4096\left(\frac{A_{s,0}}{X_0}\right)X + 0.6125A_{s,0} \qquad \text{(longitudinal cut samples)} \qquad (10)$$

$$A_s(X) = 0.5293\left(\frac{A_{s,0}}{X_0}\right)X + 0.4772A_{s,0} \qquad \text{(transverse cut samples)} \qquad (11)$$

These equations enable to consider the shrinkage effect on the drying rate of the ginger samples.

3.2 Drying characteristics

The variation of moisture content with drying time at air temperatures of 40, 60, and 80 °C and an air velocity of 1 m/s for ginger are shown in Fig. 8. The moisture content of the ginger samples decreased exponentially with time. As expected, an increase in drying air temperature reduces the time required to reach any given level of moisture content. This can be explained by increasing temperature difference between the drying air and the ginger samples and the resultant moisture (water) removal.

Drying rates were estimated based on Eqs. (7) and (11) and are shown in Fig. 9. An important influence of air temperature on drying rate is observed. As expected, an increase in air temperature increases the drying rate because higher air temperature causes a higher reduction of moisture content - in other words, at high temperatures the transfer of heat and mass is high and moisture loss is excessive. As can be seen from Fig. 9, no constant rate period was observed in the drying of ginger; the drying process took place at a falling rate period. These results are in good agreement with earlier observations (Thorat *et al*., 2012; Deshmukh *et al*., 2014). Shrinkage during drying was considered in calculating the drying rates.

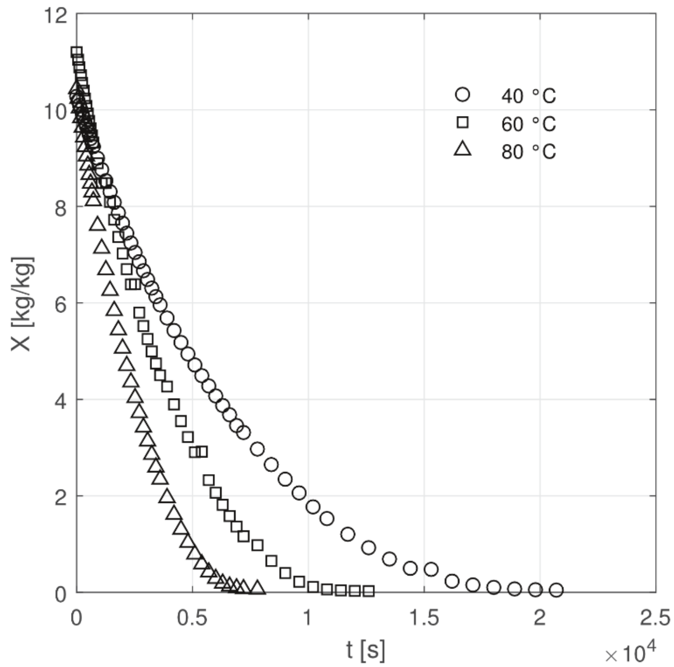

Fig. 8 Drying curves at various temperatures and an air velocity of 1 m/s (transverse cut samples).

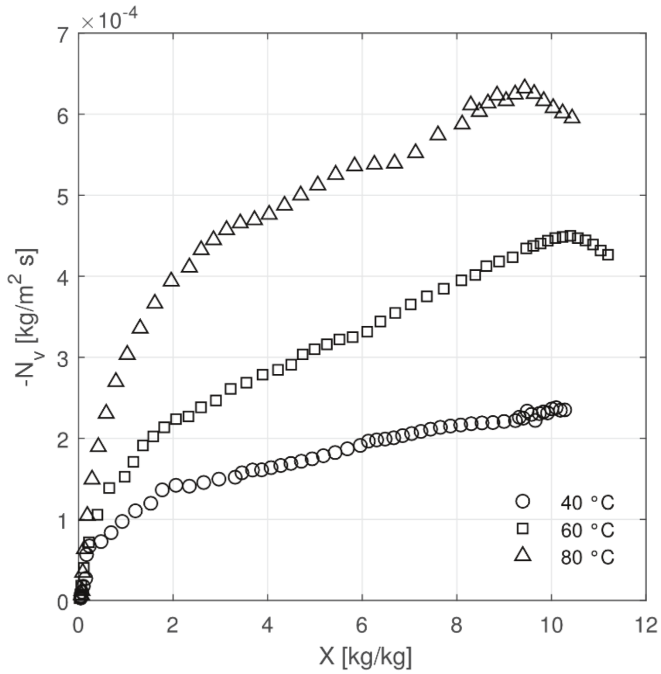

Fig. 9 Drying rate curves at various temperatures and an air velocity of 1 m/s (transverse cut samples).

The drying rate and moisture content are normalised by the constant drying rate and critical moisture content, respectively. However, for ginger no constant drying rate period was observed and another approach must be found to normalise the drying data. In this case, the critical moisture content and the maximum drying rate were determined at the beginning of the falling rate period (Bellagha *et al*., 2002; Picado *et al*., 2006).

The drying rate and moisture content are normalised by the constant drying rate and critical moisture content, respectively. However, for ginger no constant drying rate period was observed and another approach must be found to normalise the drying data. In this case, the critical moisture content and the maximum drying rate were determined at the beginning of the falling rate period (Bellagha *et al*., 2002; Picado *et al*., 2006).

In Fig. 10, experimental drying data are plotted to represent $f = f(\phi)$. Figure 10 shows that all drying curves obtained with the characteristic moisture content (ϕ) and relative drying rate (f), for the different tested conditions, fall into a tight band, thus indicating that the effect of variation in different conditions is small over the range tested.

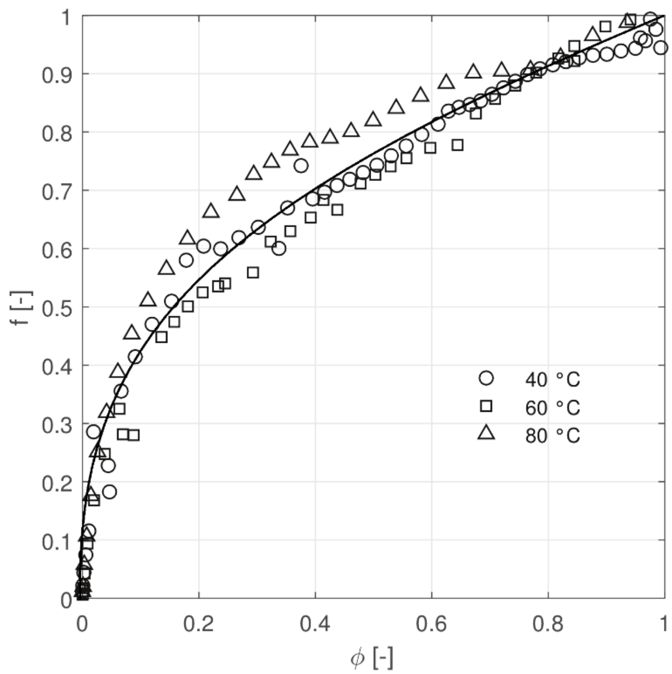

Fig. 10 Characteristic drying curve for ginger (transverse cut samples).

The regression analysis was performed using MATLAB®'s Curve Fitting Tool to find the best equation for the ginger characteristics drying curve. A polynomial equation was found to fit the best the experimental data:

$$f = -8.8163\phi^4 + 20.0166\phi^3 - 15.4952\phi^2 + 5.2620\phi + 0.0072 \qquad (12)$$

4. CONCLUSIONS

The drying of ginger (*Zingiber officinale* Roscoe) considering shrinkage was experimentally studied at air temperatures of 40, 60, and 80 °C. For the determination of shrinkage, two cutting orientations (longitudinal and transverse) were employed. The volumetric and thickness shrinkage was evaluated by direct measurement. The shrinkage showed two periods during drying. The first and the second period corresponded to a falling period and a constant period, respectively. The shrinkage of the transverse cut samples was higher than the shrinkage of the longitudinal cut samples. The shrinkage was progressive towards the centre, thus making the ginger samples take a concave shape. The results confirmed the general assumption of one-dimensional moisture transport. An equation that relates the changes in the drying area as a function of the moisture content was determined. As expected, an increase in drying air temperature reduced the time required to reach any given level of moisture content. No constant rate period was observed in the drying of ginger. The drying took place at a falling rate period. Ginger exhibited a characteristic drying curve.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support provided by the Swedish International Development Cooperation Agency (Sida).

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this article.

NOTATION

A_s	Drying area	(m^2)
d	Shrinkage exponent	(-)
D	Diffusivity coefficient	($m^2\ s^{-1}$)
f	Relative drying rate	(-)
L	Thickness	(m)
m	Mass	(kg)
N_v	Drying rate	(kg $m^{-2}\ s^{-1}$)
N_w	Drying rate, maximum at the falling rate period	(kg $m^{-2}\ s^{-1}$)
S	Shrinkage ratio	(-)
t	Time	(s)
T	Temperature	(K)
V	Volume	(m^3)
X	Moisture content, dry basis	(kg kg^{-1})
X_w	Moisture content, wet basis	(kg kg^{-1})

Greek Letters

ϕ	Characteristic moisture content	(-)

Subscripts

i	ith value	eq	Equilibrium value
cr	Critical value	s	Solid
eff	Effective value	0	Initial value
v	Volume	t	Thickness

REFERENCES

Bellagha, S., Amami, E., Farhat, A., & Kechaou, N. (2002). Drying kinetics and characteristic drying curve of lightly salted sardine (*Sardinella aurita*). *Drying Technology*, 20(7), 1527-1538. doi: 10.1081/DRT-120005866

Buvaneswaran, M., Natarajan, V., Sunil, C.K., & Rawson, A. (2022). Effect of pretreatments and drying on shrinkage and rehydration kinetics of ginger (*Zingiber officinale*). *Journal of Food Process Engineering*, 45(3), e13972. doi: 10.1111/jfpe.13972 da Silveira Vasconcelos, M., Mota, E.F., Gomes-Rochette, N.F., & Nunes-Pinheiro, D.C.S. (2019). Chapter 3.18-Ginger (*Zingiber officinale* Roscoe) In: Nabavi SM, Silva AS, editors. Nonvitamin and Nonmineral Nutritional Supplements, 235-239. doi: 10.1016/B978-0-12-812491-8.00034-5

Deshmukh, A.W., Varma, M.N., Yoo, C.K., & Wasewar, K.L. (2014). Investigation of solar drying of ginger (*Zingiber officinale*): Empirical modelling, drying characteristics, and quality study. *Chinese Journal of Engineering*, Article ID 305823, 1-7. doi: 10.1155/2014/305823

Gekas, V., & Lamberg, I. (1991). Determination of diffusion coefficients in volume-changing systems-application in the case of potato drying. *Journal of Food Engineering*, 14(4), 317-326. doi: 10.1016/0260-8774(91)90021-J

Imtiyaz, S., Rahman, K., Sultana, A., Tariq, M., & Chaudhary, S.S. (2013). *Zingiber officinale* Rosc.: a traditional herb with medicinal properties. *Cellmed Orthocellular Medicine and Pharmaceutical Association*, 3(4), 26.1-26.7. doi: 10.5667/tang.2013.0009

Jarquín, A.M. (1996). *Determinación de las curvas características de secado de algunas especies de arboles maderables de Nicaragua* [Dipl.-Ing. thesis, National University of Engineering (UNI)]. CSUCA. https://catalogosiidca.csuca.org/Record/UNI.14880

Lin, X., Xu, J.L., & Sun, D.-W. (2020). Lin, X., Xu, J.-L., & Sun, D.-W. (2020). Evaluating drying feature differences between ginger slices and splits during microwave-vacuum drying by hyperspectral imaging technique. *Food Chemistry*, 127407. doi: 10.1016/j.foodchem.2020.127407

Mendieta, R., Haerinejad, M., & Picado, A. (2015). Determination of suitable thin-layer drying models for brewer's yeast (*Saccharomyces cerevisiae*). *Nexo*, 28(2), 58-66. doi: 10.5377/nexo.v28i2.3421

Moreira, R., Figueiredo, A., & Sereno, A. (2000). Shrinkage of apple disks during drying by warm air convection and freeze drying. *Drying Technology*, 18(1-2), 279-294. doi: 10.1080/07373930008917704

Picado, A., Mendieta, R., & Martínez, J. (2006). Cinética de secado de la levadura cervecera (*Saccharomyces cerevisiae*). *Nexo*, 19(1), 49-56. doi: 10.5281/zenodo.3576375

Ren, Z., Yu, X., Yagoub, A.E.A., Fakayode, O.A., Ma, H., Sun, Y., & Zhou, C. (2021). Combinative effect of cutting orientation and drying techniques (hot air, vacuum, freeze and catalytic infrared drying) on the physicochemical properties of ginger (*Zingiber officinale* Roscoe). LWT, 144, 111238. doi: 10.1016/j.lwt.2021.111238

Sjöholm, I., & Gekas, V. (1995). Apple shrinkage upon drying. *Journal of Food Engineering*, 25(1), 123-130. doi: 10.1016/0260-8774(94)00001-P

Thorat, I.D., Mohapatra, D., Sutar, R.F., Kapdi, S.S., & Jagtap, D.D. (2012). Mathematical modeling and experimental study on thin-layer vacuum drying of ginger (*Zingiber officinale* R.) slices. *Food and Bioprocess Technology*, 5(4), 1379-1383. doi: 10.1007/s11947-010-0429-y

van Meel, D.A. (1958). Adiabatic convection batch drying with recirculation of air. *Chemical Engineering Science*, 9(1), 36-44. doi: 10.1016/0009-2509(58)87005-0