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Influence of Drying Conditions on the Effective Moisture Diffusivity and Energy Requirements of Ginger Slices

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Abstract

The thin layer drying behaviour of ginger slices in a laboratory dryer was examined. The slices of 5 mm, 10 mm and 15 mm thicknesses were dried using heated ambient air at temperatures from 40 to 70 ºC and air velocity of 1.5 m/s. The effects of drying air temperature and slice thickness on the drying characteristics, drying time and energy requirement of drying process was determined. The results have shown that an increase in the drying air temperature causes shorter drying times. Thinner slices also causes a shorter drying time. The effective moisture diffusivity values increased from 3.36814×10^{-10} m^2/s to 5.82524×10^{-9} m^2/s while the activation energy values for different slice thickness of ginger varied from 196.15 to 198.79 kJ/mol. The total needed energy varied from 735.3 to 868.5 kWh while the value of specific energy requirement varied from 3676.6 to 4342.4 kWh/kg respectively.

Keywords: drying, moisture diffusivity, energy requirements, ginger

1. Introduction

Ginger a tropical herb extensively grown for its pungently aromatic underground stem or rhizome is an important export crop in Nigeria valued for its powder, oil and oleoresin (NEPC, 1999). It possesses certain substances capable of imparting aromatic spices qualities and flavours on food and beverages. These aroma compounds partially contribute to the flavor of the fresh ginger rhizome however the oleoresin content plays an important role in the pungency of ginger (Bode & Dong, 2004). Ginger is generally sold commercially as a fresh vegetable locally without processing. However its high moisture content of about 83% makes ginger susceptible to deterioration during exportation and there if therefore the need for a preservation.

Open-air sun drying is a common means of preservation of food crops. A considerable part of dried fruits and vegetables utilized worldwide are sun dried in the open without technical aids (Murthy, 2008). However, sun drying of crops in the open air has its limits if used for large-scale production. This is because of some of the constraints of sun drying which include difficulty in the proper control of the drying process, weather variations, high labour costs, large land areas needed for drying, insect infestation, presence of contaminants like dust and other foreign materials to mention a few of the constraints. Solar and other forms of hot air drying have been proposed to help overcome the constraints of sun drying. Design, construction and operation of drying systems can only be done effectively if the drying kinetics of the food materials to be dried, models that can simulate the process and the energy requirements of the drying process are known.

Determination of physical and thermal properties of food crops is essential for dryer design. These properties which include moisture diffusion, energy of activation and energy consumption and their effect on the thin layer drying of food crops have been investigated for a number of fruits and vegetables which include figs, seedless grapes, tomatoes, pumpkin slices, plum, hazelnuts, grapes, candle nuts and apple pomace (Bablis & Belessiotis, 2004; Doymaz & Pala, 2002; Doymaz, 2007a, 2007b; Goyal et al., 2007; Ozdemir & Devres, 1999; Pahlavanzadeh et al., 2001; Tarigan et al., 2006; Wang et al., 2007). However, little or no work has been done to determine the drying kinetics and the energy requirements in thin-layer drying of ginger. This study is therefore carried out to calculate and to evaluate the effect of the air temperature and slice thickness on the effective moisture diffusivity, energy of activation and energy consumption for thin-layer drying of ginger.

2. Material and Methods

2.1 Experimental Procedure

Fresh ginger (*Zingibar officinale*) was purchased at a local market in Ibadan, Nigeria. Care was taken to select ginger without any defect having of average thickness of 15 ± 0.2 mm. The ginger rhizomes were washed in cold water to remove soil and dust particles. The washed ginger rhizomes were peeled and cut with knives into slices of 10 mm and 5 mm thickness. Some of the samples were peeled and dried whole which gave a mean slice thickness of 15 mm.

The peeled samples were placed in a locally fabricated drier preset at temperatures of 40, 50, 60 and 70 ºC and a constant air velocity (1.5 ms^{-1}). The laboratory dryer consists of an airflow control unit, a heating and heating control unit, an electrical fan and drying chamber (Figure 1). For each experimental run, the dryer run for about 2 hours before the commencement of experiment to stabilize it at the specified air conditions before the drying of the samples began. The initial moisture content was determined using the method of Doymaz (2005) and an average initial moisture content of 72% wet basis was obtained.

Ginger samples were loaded into the drier and removed at regular intervals until the weight became constant after three consecutive weighing, indicating equilibrium conditions. Initially weighing of the samples was made at shorter intervals of approximately 30 min, and at later stages of drying the weighing intervals was increased to 1 h. Weighing was done using a precision digital balance (PH Mettler) with an accuracy of ± 0.01 g.

Drying of the samples continued until a constant weight was reached. The sample weights at different time intervals were recorded throughout the drying process. The weights recorded during drying and the initial moisture content (wet basis) was used as a basis to calculate the moisture contents (dry basis) for each drying time interval. These calculated moisture contents (d.b.) were used as the basic data for further analysis, rather than the actual weight of the sample. Drying experiments were done in triplicates and the average moisture content value for each pretreatment was used to calculate the moisture ratio.

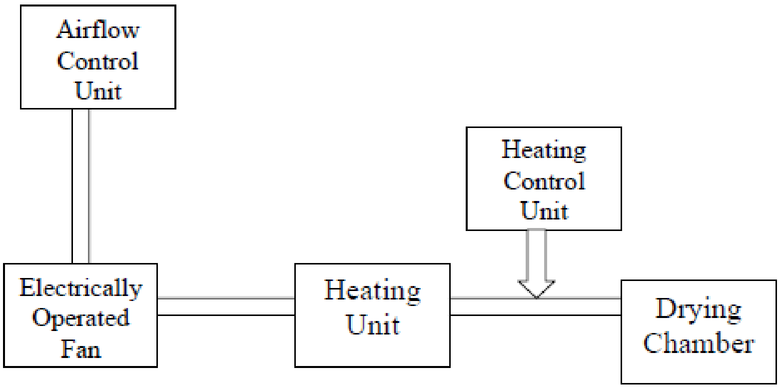


Figure 1. Schematic diagram of laboratory dryer

2.2 Theoretical Considerations

The graph of moisture ratio with drying time was used to represent the experimental drying data. This is because since the initial value for moisture ratio is one for each of the experiments, the moisture ratio curve will explain the drying behaviour better than that of moisture content curve. The moisture ratio was calculated using the equation below:

$$M_R = \frac{M - M_e}{Mo - M_e} = \exp(-Kt) \tag{1}$$

where M is moisture content at any time t, M_e is equilibrium moisture content and M_o is initial moisture content

The moisture ratio values were used to plot the drying curves of the dried ginger samples.

The Fick's diffusion equation developed for solid objects with slab geometry by Crank (1975) was applied to the experimental data on the assumption that there is uniform initial moisture distribution and negligible external resistance. The equation is in the form:

$$MR = \frac{(M - M_e)}{M_o - M_e} = \frac{8}{\pi^2} \exp(\frac{-\pi^2 D_{eff} t}{L^2}) \tag{2}$$

The slope of the plot of ln [(M-M$_e$)/ (M$_o$-M$_e$)] against time (t) was used to determine the moisture diffusivity for the different drying methods.

The energy of activation was calculated by using an Arrhenius type Equation,

$$De_{ff} = D_o \exp\left(- \frac{E_a}{R_g T_{abs}} \right) \tag{3}$$

where Ea is the energy of activation, Rg is universal gas constant (8.3143 kJ/mol), T_{abs} is absolute air temperature (K), and D_0 is constant.

Equation (3) can be linearized by applying the logarithms as

$$LnD_{eff} = LnD_o - \frac{E_a}{R_g} \cdot \frac{1}{T_{abs}} \tag{4}$$

From Equation (4), a plot of Ln D_{eff} versus 1/Tabs gives a straight slope of K_2

$$K_2 = \frac{E_a}{R_g} \tag{5}$$

The coefficient of determination (R^2) was determined by fitting the Equation 5 into the experimental data using linear regression analyses. The total needed energy for drying one charge of the heater and energy requirements for drying 1 kg of fresh ginger slices during each drying experiments was calculated as follows:

$$E_t = A \nu \rho_a c_a \Delta T D_t \tag{6}$$

where E_t is total needed energy for drying for each experimental condition; A is tray area; ν is air velocity; ρ_a is air density; Dt is total drying time; ΔT is temperature differences (difference between drying temperature and ambient temperature) and c_a is the specific heat of air

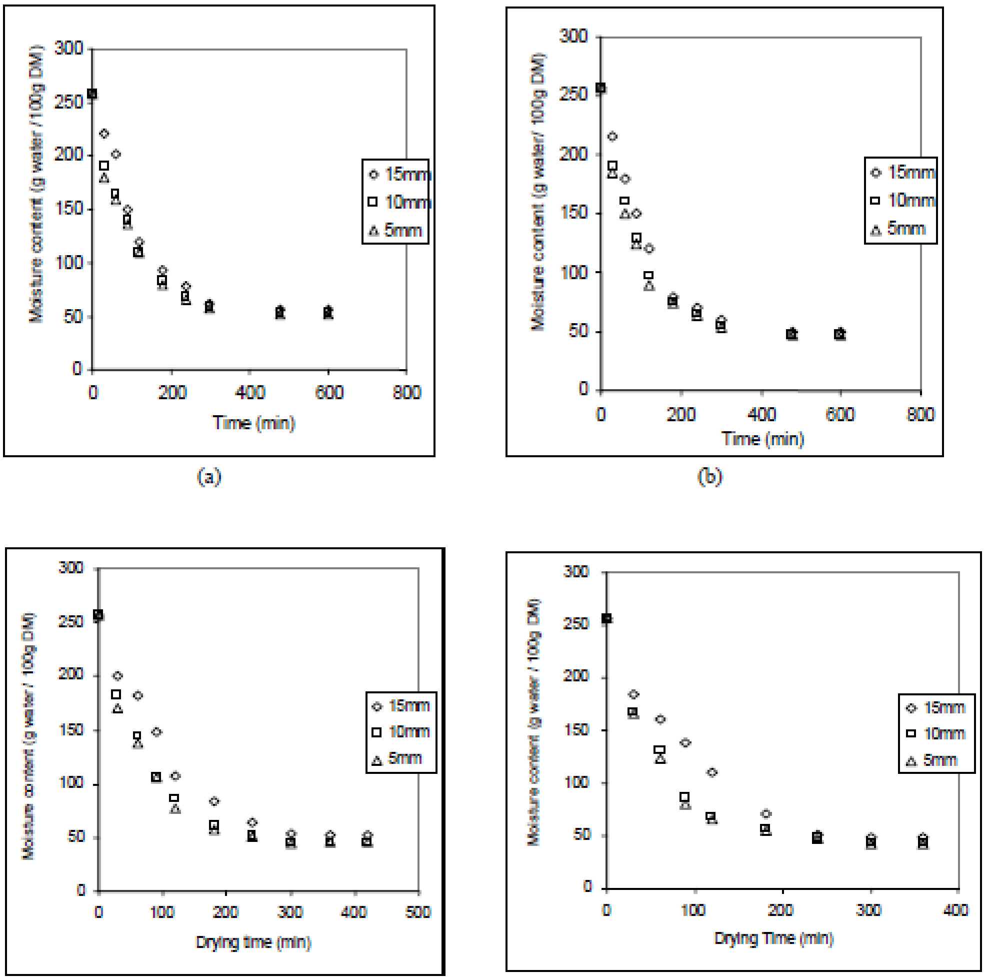
$$E_{kg} = \frac{E_t}{W_o} \tag{7}$$

where E_{kg} is specific energy requirement and W_o is initial weight.

3. Results and Discussion

3.1 Drying Kinetics

The variation of moisture content with drying time for ginger slices 15 mm, 10 mm and 5 mm thick within the temperature range of 40 to 70 ºC are indicated in Figure 2. The figures also show clearly that the drying time decreased with increase in drying air temperature. The drying time required to reach a moisture content of 0.5% dry basis (50 g water/100g DM) at drying temperatures of 40 and 50 ºC was approximately twice and one and a half times that which is required for a drying temperature of 60 and 70 ºC respectively. This is similar to the results for apples, celery and apricot (Meisami-asl & Rafiee, 2009; Román & Hensel, 2011; Mirzaee et al., 2010). The same trend was observed with increase in thickness of the ginger slices. Samples of 5 mm thickness had the lowest drying curves followed by 10 mm while samples 15 mm thick had the highest drying curve. This is an indication that thicker samples had lower drying rates. This is due to the distance moisture travels to the food surface which is more in the case of thicker slices hence drying is slower.

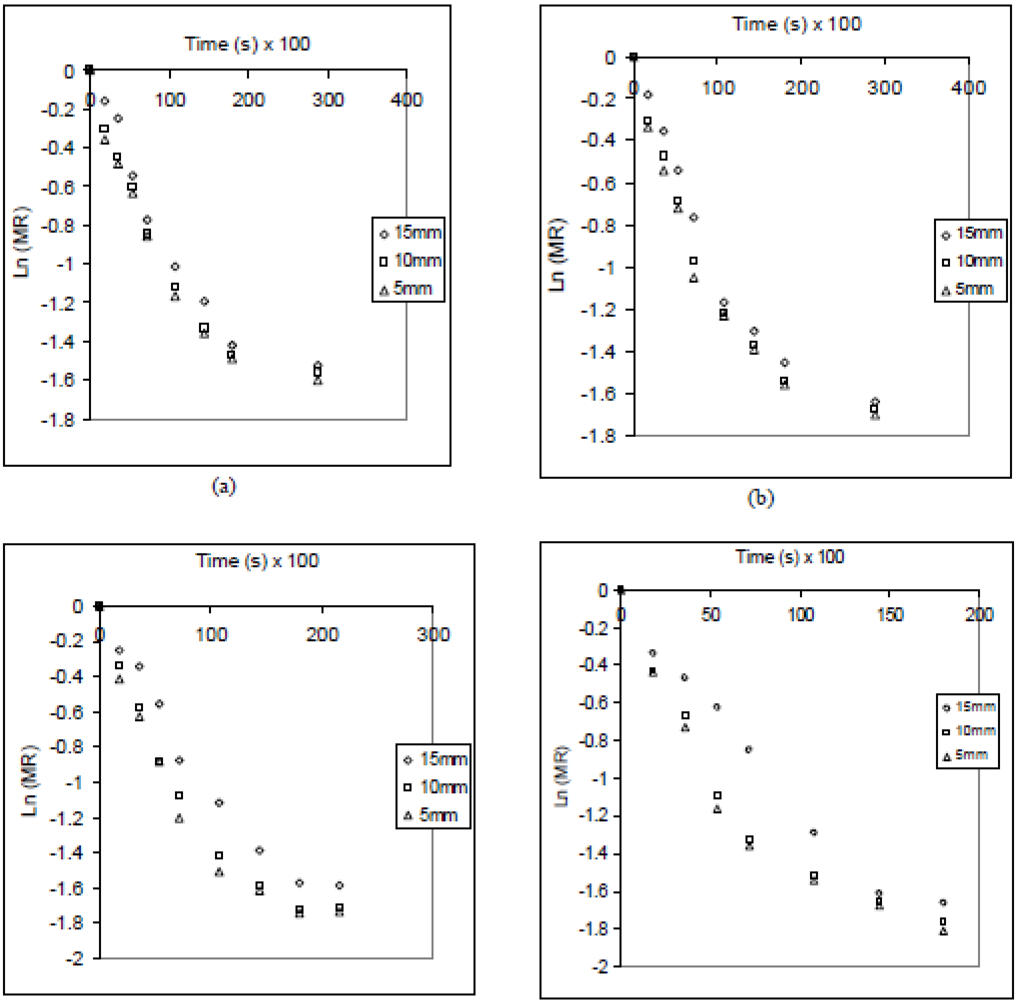


(a) (b)

(c) (d)

Figure 2. Drying curve of ginger dried at (a) 40 ºC (b) 50 ºC (c) 60 ºC (d) 70 ºC

The graphs of Ln (MR) against time for the different slice thickness and temperatures are shown in Figure 3 and the figure show graphs of straight lines. This is because the drying of ginger took place in the falling rate period thus indicating that the drying process is controlled by liquid diffusion. The increase in temperature is observed to increase the slope of the straight lines thus indicating an increase in effective moisture diffusivity as temperature increases. This is similar to the observations for cocoa, berberis fruit, red chillies, apples, tomatoes and kale (Ndukwu, 2009; Aghbashlo et al., 2008; Kaleemullah & Kailappan, 2005; Goyal et al., 2008; Doymaz, 2007a; Mwithiga & Olwal, 2005). The observation for slice thickness is similar, as the slice thickness decreased, the slope decreases thus decreasing effective moisture diffusivity. This is similar to the report obtained for potato and yam (Akpinar et al., 2003; Falade et al., 2007). The minimum value of moisture diffusivity was 3.36814 × 10^{-10} m^2/s for slices of 5mm, dried at 40 ºC while the maximum value of 5.82524 × 10^{-9} m^2/s was obtained for slices of 15 mm thickness (whole) dried at 70 ºC (Table 1). The effective moisture diffusivity is within the range of 10^{-11} to 10^{-9} m^2/s for food materials. The values of Deff plotted against temperature for the various slice thickness are shown in Figure 4. Linear equations were fitted for the calculated values of Deff. Fitted equation and related R^2 are reported in Table 2. In Figure 4 the minimum value of Deff was obtained from the minimum drying temperature, while an increase in slice thickness increases the value of Deff at constant drying temperature. The Deff values obtained at 40 and 50 ºC for all the thicknesses were not significantly different while the values obtained at the other drying temperatures considered were significantly different.



(a) (b) (c) (d)

Figure 3. Ln (MR) against drying time (s) for thin-layer drying of ginger slices
at (a) 40 °C (b) 50 °C (c) 60 °C (d) 70 °C

Table 1. Effective moisture diffusivity for the various drying experiments

Slice thickness (mm)	Temperature (°C)			
	40	50	60	70
15 mm	3.147 E-09c*	3.34 E-09c	4.789 E-09b	5.825 E-09a
10 mm	1.337 E-09c	1.424 E-09c	2.126 E-09b	2.459 E-09a
5 mm	3.368 E-10c	3.517 E-10c	5.235 E-10b	6.218 E-10a

* Values with same superscript in the same row are not significantly different ($P < 0.05$).

3.2 Activation Energy

A plot of Ln Deff versus 1/Tabs is indicated in Figure 5 and activation energy, Ea is obtained from Equation 5. The Ea values for different slice thickness of ginger are reported in Table 2 and the values which are not significantly different (at $p < 0.05$) varied from 196.15 to 198.79 kJ/mol. These values are higher than that of the Ea values for figs which varied from 30.8 to 48.47 kJ/mol (Babalis & Belessiotis, 2004), for apricots from 24.01 to 25.0 kJ/mol (Mirzaee et al., 2010) and that of berberis fruit which varied from 110.837 to 130.61 kJ/mol for different values of air velocities (Aghbashlo et al., 2008). The values obtained for ginger are however within the range of 146.40 to 232.45 kJ/mol obtained for Jerusalem artichoke tubers (Lili et al., 2013) and lower than of 422.79 ± 0.52 kJ/mol obtained for taro (Abubakar et al., 2012). This is because water that exists in the form of chemical absorptions in food materials (which is the case for ginger) requires more energy to exhaust than water that exists on the surface of food materials.

Table 2. Fitted equation for Deff and Energy of activation value for ginger slices

Slice thickness (mm)	Equation	R^2	E_a (kJ/mol)	R^2
15 mm	Deff=0.949T + 1.905	0.9336	196.15a*	0.9317
10 mm	Deff=0.407T + 0.82	0.9255	198.26a	0.9187
5 mm	Deff=0.1027T + 0.202	0.9231	198.79a	0.9153

* Values with same superscript in the same column are not significantly different ($P < 0.05$).

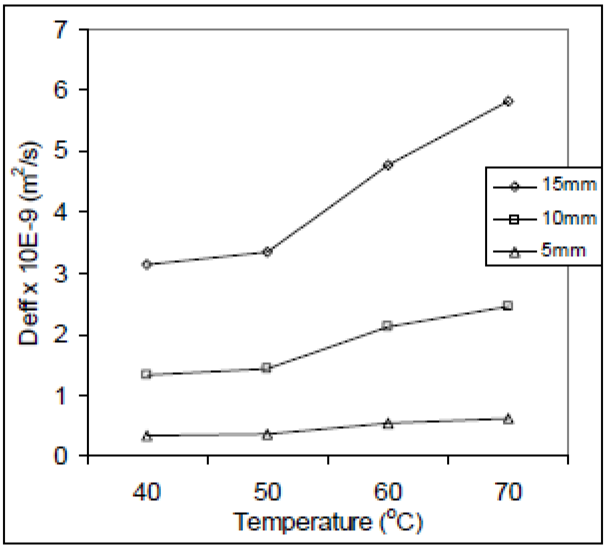


Figure 4. Deff against drying temperature at different slice thickness for thin-layer drying of ginger

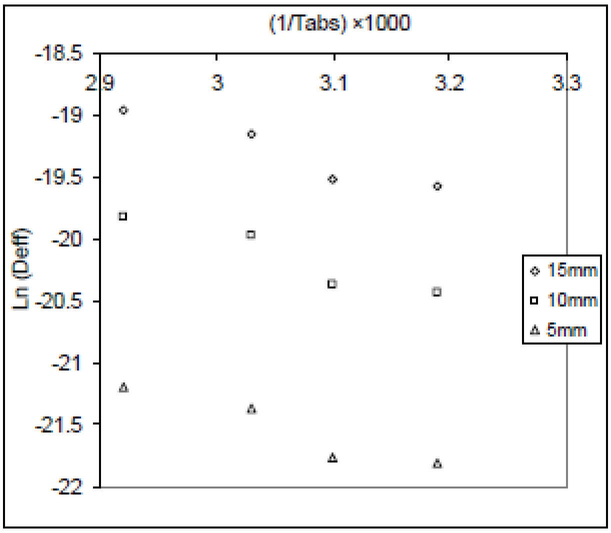


Figure 5. Ln (Deff) versus 1/Tabs at different slice thickness for thin-layer drying of ginger

3.3 Energy Requirements

The total energy needed for drying at each condition of dryer condition was determined using Equation 6 and the energy requirements for drying 1kg of ginger was determined for each experimental condition using Equation 7. The total needed energy (Figure 6) varied from 735.3 kWh to 868.5 kWh, the lowest value was obtained with ginger slices of 5 mm thickness at a drying air temperature of 70 ºC and the highest value was from ginger slices of 15 mm thickness at a drying air temperature of 60 ºC. The maximum and minimum value of specific energy requirement (Figure 7) of 4342.4 kWh/kg and 3676.6 kWh/kg for ginger drying was obtained at drying air temperature of 60 ºC and 70 ºC respectively. The highest total energy needed was obtained for thickest samples (i.e 15 mm) and the lowest was for 5mm samples. This is probably due to the fact that the energy utilized to transfer heat to the internal regions of the slice is higher since the heat transfer distance is higher. This will result in a longer drying time (since it is dependent on the drying time as indicated in Equation 6. The lowest total energy needed and minimum value of specific energy requirement was obtained from samples dried at 70 ºC. This is probably as a result of the greater heat transfer and water vapour pressure deficit that occurs when drying is done at higher temperatures (Rayaguru & Routray, 2012). This gives rise to a greater uptake of air and evaporation is achieved in a shorter time thus reducing the amount of energy needed.

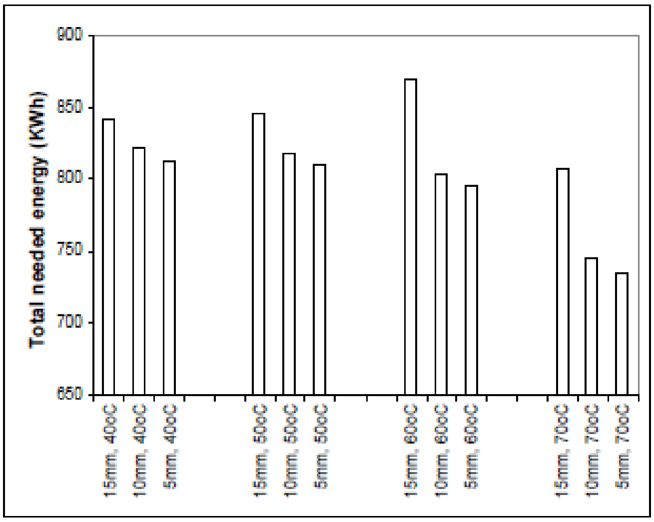


Figure 6. Total energy needed for drying of ginger slices

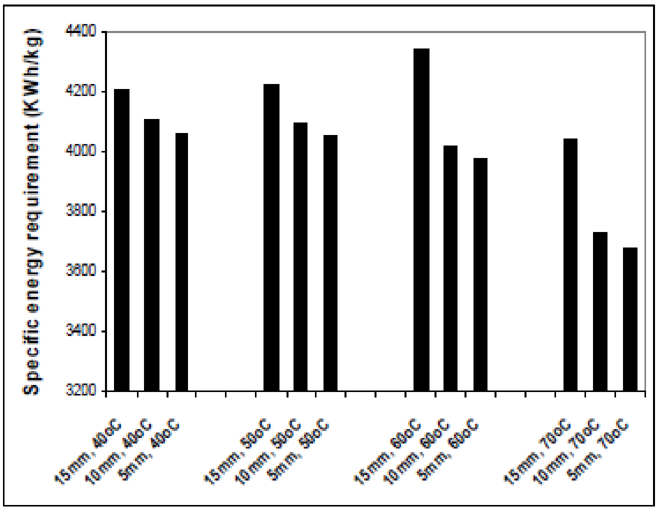


Figure 7. Energy requirements for drying 1 kg of ginger

4. Conclusion

The drying time and rate decreased with increase in drying air temperature from 40 to 70 ºC, while drying rate decreased with increase in slice thickness from 5 mm to 15 mm. The drying of ginger was observed to take place only in the falling rate period an indication that liquid diffusion controlled the drying process. The value of effective moisture diffusivity varied from 3.36814×10^{-10} m^2/s to 5.82524×10^{-9} m^2/s for ginger slices of thicknesses considered in this study. The value of effective moisture diffusivity increased with increase in temperature and decrease in slice thickness. The activation energy Ea for ginger slices varied from 196.15 to 198.79 kJ/mol. The value of total needed energy for thin-drying of ginger slices at different levels of air temperatures varied from 735.3 to 868.5 kWh for the experimental conditions considered. Specific energy requirement calculated for ginger slices varied from a minimum of 3676.6 to a maximum of 4342.4 kWh/kg.

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Nomenclature

A	tray area (m^2)
C_a	specific heat of air (kJ/kg ºC)
D_{eff}	effective moisture diffusivity (m^2/s)
D_o	constant (dimensionless)
D_t	total drying time (h)
E_a	energy of activation (kJ/mol)
E_{kg}	specific energy requirement (kWh/kg)
E_t	energy needed (kWh)
K_1, K_2	slope of straight line
L	half of the slab thickness (m)
M_e	equilibrium moisture content of sample (kg water/ kg dry solid)
M_o	the initial moisture content (kg water/kg dry solid)
M	the moisture content at any time (kg water/kg dry solid)
M_R	moisture ratio (dimensionless)
R_g	universal gas constant (8.3143 kJ/mol)
T	air temperature (^{o}C)

T_{abs}	absolute air temperature (K)
W_0	initial weight (g)
t	time of drying (s)
R^2	correlation coefficient
ρ_a	air density (kg/m^3)
ΔT	temperature differences (^oC)

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