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ORIGINAL RESEARCH PAPER

EFFECT OF MOISTURE CONTENT AND TEMPERATURE ON THERMAL BEHAVIOUR OF SESAME SEED

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The specific heat, thermal diffusivity and thermal conductivity of two varieties (white and brown) of sesame seeds were evaluated as a function of moisture content and temperature. The experiments were conducted in the temperature range of 25-70˚C and the moisture content range of 3.86-19.83% (dry basis) for white and 3.07-18.99% (dry basis) for brown varieties. The specific heat of white and brown sesame seeds ranged 1062-3058 and 906-2958 J/(kg·˚C), respectively. Thermal diffusivity and thermal conductivity values also increased with increasing either moisture content or temperature. Thermal diffusivity varied between 4.66×10^{-8} and 8.59×10^{-8} m^2/s for white and 4.36×10^{-8}-8.08×10^{-8} m^2/s for brown varieties. Thermal conductivity ranged 0.031-0.149 and 0.023-0.135 W/(m·˚C) for white and brown varieties, respectively. Results showed that the moisture content and temperature had significant effects ($p\leq0.01$) on the studied properties.

Keywords: modelling, postharvest, specific heat, thermal conductivity, thermal diffusivity

Introduction

Sesame (*Sesamum indicum* L.) is an oilseed herbaceous crop of the *Pedaliaceae* family. It is widely cultivated in many parts of the world for a long time owing to its high content of excellent quality oil (44-58%) and protein (18-25%) (Saydut *et al*., 2008). Furthermore, the amino acid composition of the sesame seeds is unique and extraordinary due to its high content of sulphur-containing amino acids (methionine and cysteine) and low content of lysine (Orruño and Morgan, 2007). The study of this crop is nowadays of growing interest because of extending its oil application. The extracted oil of sesame seed has been used as a healthy food up to raw material for the production of some industrial products including ointment, paints, margarine, varnishes (Tunde-Akintunde and Akintunde, 2004) as well as a source of renewable energy in the form of biodiesel fuel (Saydut *et al*., 2008).

A profound understanding of engineering properties of agricultural crops is indispensable for improving the design of related apparatus and analyzing the behaviour of the product during industrial processes (Singh and Kotwaliwale, 2010). From scientific and industrial standpoints, the knowledge of thermal properties such as specific heat, thermal conductivity and thermal diffusivity is essential to modelling, optimization and design of processes and processing equipment for the operations based on thermal treatments (Bitra *et al.*, 2010). These parameters are also essential for simulating and modelling heat transfer phenomena in the grinder (Singh and Goswami, 2000) and analyzing heating and cooling process for postharvest pest control (Tang *et al*., 2007).

Drying the sesame seed is extremely momentous to enable preservation, transport and sale. Accordingly, it is necessary to design and simulate accurately the drying systems for sesame seeds. The awareness of thermal properties of sesame seed is fundamental to foresee seed temperature and rate of drying. This prediction is vital for suitable storage without losing the quality or causing damage to seed structure (Hobani and Tolba, 1995).

Different ways for measuring thermal conductivity, thermal diffusivity and specific heat of food and biological materials are described in the literature. The transient heat flow methods using the line heat source has been used by many researchers for determination of thermal conductivity of plant materials such as gram (Dutta *et al*., 1988), barley (Hobani and Tolba, 1995), cumin seed (Singh and Goswami, 2000), rice starch (Fang *et al*., 2000), radish and alfalfa seeds (Yang and Zhao, 2001), borage seed (Yang *et al*., 2002), sugarbeet roots (Tabil *et al*., 2003), minor millet grains and flours (Subramanian and Viswanathan, 2003), berberis fruit (Aghbashlo *et al*., 2008), pumpkin seed (Kocabiyik *et al*., 2009), pigeonpea (Singh and Kotwaliwale, 2010), peanut pods, kernels and shells (Bitra *et al*., 2010), and jatropha kernel (Sirisomboon and Posom, 2012). Besides, a number of researchers have determined the thermal conductivity using the steady state heat flow methods like sheanut kernel (Aviara and Haque, 2001), guna seed (Aviara *et al*., 2008), roselle seeds (Bamgboye and Adejumo, 2010), and red lentil seed (Gharibzahedi *et al*., 2013). The thermal diffusivity of a material is usually measured using the transient method of Dickerson (1965). This route has been used by several researchers to study barley (Hobani and Tolba, 1995), soursop pulp (Jaramillo-Flores and Hernandez-Sanchez, 2000), minor millet grains and flours (Subramanian and Viswanathan, 2003), and jatropha kernel (Sirisomboon and Posom, 2012). Furthermore, a number of researchers have determined the thermal diffusivity using the specific heat, thermal conductivity and bulk density of biomaterials such as gram (Dutta *et al*., 1988), cumin seed (Singh and Goswami, 2000), sheanut kernel (Aviara and Haque, 2001), guna seed (Aviara *et al*., 2008), pumpkin seed (Kocabiyik *et al*., 2009), roselle seeds (Bamgboye and Adejumo, 2010), pigeon pea (Singh and Kotwaliwale, 2010), peanut pods, kernels and shells (Bitra *et al*., 2010), and red lentil seed (Gharibzahedi *et al*., 2013). The specific heat of several grains, seeds and kernels has been determined using Differential Scanning Calorimetery (DSC), including cumin seed (Singh and Goswami, 2000), borage seed (Yang *et al*., 2002), and jatropha kernel (Sirisomboon and Posom, 2012). Furthermore, other researchers used the method for determination of specific heat of mixtures of materials such as gram (Dutta *et al*., 1988), sheanut kernel (Aviara and Haque, 2001), sugar beet roots (Tabil *et al*., 2003), minor millet grains and flours (Subramanian and Viswanathan, 2003), pistachio nuts (Razavi and Taghizadeh, 2007), guna seed (Aviara *et al*., 2008), berberis fruit (Aghbashlo *et al*., 2008), pumpkin seed (Kocabiyik *et al*., 2009), roselle seeds (Bamgboye and Adejumo, 2010), pigeon pea (Singh and Kotwaliwale, 2010), peanut pods, kernels and shells (Bitra *et al*., 2010), and red lentil seed (Gharibzahedi *et al*., 2013).

Despite the extensive literature on the thermal properties of various agricultural produce, the authors could not find any published work concerning the specific heat, the thermal conductivity or the thermal diffusivity of the sesame seed and its variation due to different moisture contents and temperatures. Therefore, the objective of this work was to determine and develop empirical models for prediction of these three thermal properties of white and brown sesame seeds as a function of moisture content and temperature. Application of the investigated mathematical models in the design of the thermal process equipment could directly affect the quality of extracted oil, and/or leading to low operation/processing cost and energy.

Materials and methods

Sample preparation

The samples of white and brown sesame seed were provided from a local market in Mashhad city of Iran. The samples were manually cleaned. The initial moisture content of the samples was determined by oven drying at 130 ± 1˚C for 6 h (Bitra *et al*., 2010). The samples at the desired moisture levels were prepared by adding calculated amounts of distilled water, thorough mixing and then sealing in separate polythene bags (Gharibzahedi *et al*., 2013). The samples were kept at 4 ± 1˚C in a refrigerator for a week, for thorough and uniform distribution of moisture (Singh and Goswami, 2000). Before conducting each experiment including moisture content determination, the required amount of samples were taken out of the refrigerator to allow them to reach an equilibrium with room temperature for about 2 h (Bitra *et al*., 2010; Subramanian and Viswanathan, 2003; Gharibzahedi *et al*., 2013). All tests were conducted in the laboratory under air pressure of the room (675 mm Hg), ambient temperature of about 20 ± 1˚C and relative humidity of 45-50%. Thermal properties for raw sesame were investigated in the temperature range of 25-70˚C and the moisture content of 3.07-18.99 (d.b., brown variety) and 3.86-19.83% (d.b., white variety) since harvesting to storage operations of sesame is carried out in these ranges.

Specific heat measurement

The technique of mixtures, which is apposite technique for granular materials (Kocabiyik *et al*., 2009; Mohsenin, 1980), was applied to assess the specific heat of sesame seeds. The selection of this method was based on its simplicity, accuracy of results and wide acceptability (Tabil *et al*., 2003).

The applied setup (Figure 1) comprised a calorimeter, capsule, two thermocouples (0.713 mm ϕ; ± 0.4% ˚C accuracy), and temperature indicator. The calorimeter, which was fabricated in the laboratory conditions for this study, was constructed from a flask, plastic external casing, rubber O-ring, and plastic screw lid. A similar laboratory setup was used by Subramanian and Viswanathan (2003), Razavi and Taghizadeh (2007) and Aghbashlo *et al*. (2008).

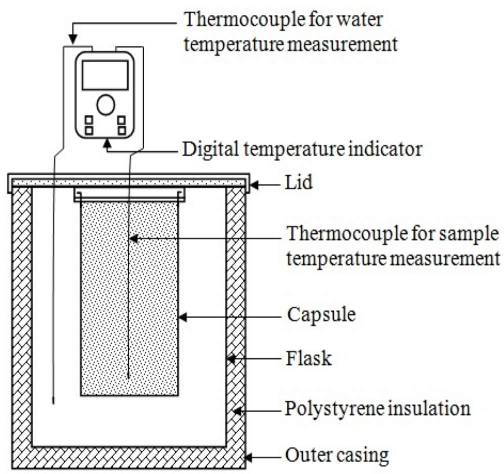

Figure 1. Schematic of applied setup for measuring specific heat

The specific heat of sesame seed varieties was obtained using the method described by Razavi and Taghizadeh (2007). To determine the specific heat of the sesame seeds, the specific heat of flask calorimeter and capsule had to be measured firstly. For this purpose a measured mass of hot distilled water was added to flask calorimeter that containing a known quantity of cold distilled water and then the lid was closed. After reaching to the equilibrium condition, when there was no temperature change, measurement was stopped. The specific heat capacity of flask calorimeter was estimated using the following heat balance equation (Aviara and Haque, 2001; Razavi and Taghizadeh, 2007):

$$C_f = \left[M_{cw}C_w(T_e - T_{cw}) - M_{hw}C_w(T_{hw} - T_e)\right]/(T_{hw} - T_e) \quad (1)$$

where: C_f and C_w – specific heats of flask calorimeter and water, respectively (J/(kg·˚C)); M_{cw} and M_{hw} – mass of cold and hot water, respectively (kg); T_e – equilibrium temperature of the mixture of hot and cold water (˚C); T_{cw} and T_{hw} – initial temperature of cold and hot water, respectively (˚C).

The heat capacity test of the calorimeter was repeated three times. The average specific heat of the calorimeter was used to determine the specific heat of the samples. To determine the specific heat capacity of capsule, the hot capsule was added to the flask that containing a known amount of cold distilled water, then the lid was closed, the temperature of inside the calorimeter was being checked until reaching to stable reading. Then, the heat capacity of capsule was computed using the relationship given by Razavi and Taghizadeh (2007), as follows:

$$C_c = \left((C_f + M_{cw}C_w)(T_e - T_{cw})\right) / (T_c - T_e) \tag{2}$$

where: C_c – specific heat of capsule (J/(kg·˚C)); T_e – equilibrium temperature of capsule, flask and cold water (˚C); T_c – initial temperature of capsule (˚C).

The test was repeated three times. To determine the specific heat of sesame seeds, the capsule containing sample of known mass was placed inside the oven till reaching the desired temperature. The filled capsule was then rapidly transferred to the calorimeter which contained a specific mass of distilled water at a specific low temperature. As soon as the capsule was added, the lid was closed and the temperatures of both thermocouples were monitored until approaching the same temperature for both of them. Then the equilibrium temperature was recorded and the specific heat was calculated as below (Razavi and Taghizadeh, 2007; Aghbashlo *et al*., 2008):

$$C_s = \frac{(C_f + M_{cw}C_w)(T_e - T_{cw}) - C_c(T_m - T_e)}{M_m(T_m - T_e)} \times 4.1868 \tag{3}$$

where: C_s – specific heat of sample (J/(kg·˚C)); T_e – equilibrium temperature of mixture (˚C); T_m – initial temperature of sample (˚C); M_m – mass of sample (kg).

The experiments were repeated three times for each moisture level and temperature range, and the average values of specific heat are reported.

Thermal diffusivity measurement

For thermal diffusivity measurement, the method of Dickerson (1965) was followed. This technique is based on the transient heat transfer conditions whereby temperatures of the sample increase linearly with time. An experimental apparatus similar to the one employed by Hobani and Tolba (1995) was built (Figure 2). It consisted of a water bath, temperature control unit, heater, stirrer, cylinder and two thermocouples (± 0.1˚C accuracy). The box containing water was insulated with glass wool to minimize thermal losses from water bath to its surrounding. To homogenize the temperature between heater and cylinder, water in the water bath was stirred by placing a mechanical stirrer operated electrically with a changeable speed motor. The cylinder which was made from copper with 48 mm internal diameter, 192 mm long, 0.35 mm thickness and a length to diameter ratio of 4 to eliminate radial heat loss. Hobani and Tolba (1995) reported that heat transfer is occurred only in the radial direction when the ratio of length to diameter of the cylinder lies between 3:1 and 6:1. The top and bottom of the cylindrical sample holder were closed with 10 mm thick Teflon plates to also ensure only radial heat transfer. The top plate was detachable to enable the samples to be placed in the cylinder. Two thermocouples (Type PT 100) (06/11, Vesta, China) were used to increase the accuracy. The thermocouples were calibrated prior to the experiments with a mercury thermometer. One thermocouple was attached to the outer surface of the cylinder to monitor its temperature by a temperature controller (SU-105 PP, Samwon Eng., Korea).

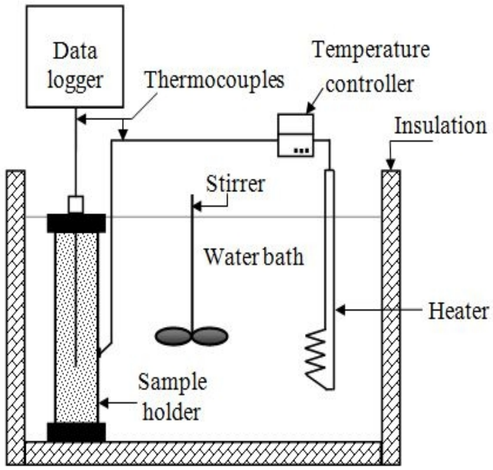

Figure 2. Schematic diagram of thermal diffusivity apparatus

For the performed trial, the sesame seeds were poured in the cylinder. Then, cylinder was closed by the top cap with a hole exactly in the centre and afterward, the second thermocouple was inserted into the bulk of sesame seed through the hole. The area around the hole was dabbed with glue to ensure sealing. The cylinder was then immersed into the agitated water bath whose temperature was kept constant by a thermostat at the desired temperature during the experiment. Specifying the temperature of cylinder centre and the time required to achieve the equivalent temperature with surface of the cylinder was obligatory. For this reason, the increase in temperature with time is recorded with the help of a data logger multi-type thermometer (TM-946, Lutron, Taiwan) at 0.1˚C intervals. The curve log $((T_s-T_o)/(T_s-T))$ was drawn against the elapsed time, where T_s is the temperature on surface of tube in ˚C, T_o is the initial temperature of the sample in ˚C, and T is the temperature in centre of the tube in ˚C. Thereafter, the best fitting straight line portion on the thermograph was chosen. The slope of the line was determined by a linear regression on the selected linear segment and it was used to calculate the bulk thermal diffusivity. Meantime, the slope with the coefficient of determination (R^2) value of less than 0.99 was not used in the thermal diffusivity determination. Eventually, the thermal diffusivity (α) value was calculated by using the following formula according to Jaramillo-Flores and Hernandez-Sanchez (2000):

$$\alpha = \frac{0.398}{\left[\frac{1}{r^2} + \frac{0.427}{h^2}\right]\tau} \tag{4}$$

where: r is the inner radius of the finite copper tube (m); h is the half-height of the tube (m); τ is the slope obtained from the heat penetration curve or the same time constant (s).

Each assay was replicated 3 times at each moisture level, temperature level, and per seed type and the mean values were reported.

Thermal conductivity measurement

Thermal conductivity of sesame seed was directly calculated using the following relationship (Mohsenin, 1980):

$$k = \alpha \rho_b C_s \tag{5}$$

where: k – thermal conductivity of sample (W/(m·°C)); α – thermal diffusivity of sample (m^2/s); ρ_b – bulk density of sample (kg/m^3); C_s – specific heat of sample (J/(kg·°C)).

To determine the bulk density that was substituted in the above relationship, hundred-millilitre beaker was filled completely with sesame seeds. The excess seeds were removed by sweeping the surface of the cylinder. The cylinder was tapped several times and was refilled. Then, its content was weighed by an electronic balance. The ratio of sesame seeds weight to the cylinder volume gave the bulk density (Mohsenin, 1980). The average of 10 replications was taken for each moisture content level.

Statistical analysis

Analysis of variance (ANOVA) was carried out to test the significance ($P<0.05$) of the effect of moisture content and temperature on the thermal attributes using SPSS 17 software. Also, multiple regression analysis was employed to describe the relationship of moisture content and temperature with respective thermal properties.

Results and discussion

Bulk density

The values of bulk density of white and brown sesame seeds decreased significantly ($p<0.05$) from 630.49 to 565.49 and 588.52 to 564.45 kg/m^3 with increase in their moisture contents, respectively. This behaviour may be attributed to the less weight gain due to the added moisture in spite of volumetric expansion of the seeds (Singh and Kotwaliwale, 2010). The white sesame variety represented higher bulk density values than that of the brown sesame variety at all moisture content levels. A linear relationship between the moisture content and the bulk density was found as below:

$$\rho_{\mathrm{bw}} = -4.0997M + 647.01, R^2 = 0.999 \tag{6}$$

$$\rho_{\mathrm{bb}} = -1.5976M + 594.65, R^2 = 0.972 \tag{7}$$

where: ρ_{bw} and ρ_{bb} – bulk densities of white and brown sesame seeds, respectively (kg/m^3); M – moisture content (% d.b.).

Specific heat

The effect of moisture content and temperature on specific heat of white and brown sesame seeds is presented in Figure 3. As it can be seen in this figure, the specific heat increased with increasing either temperature or moisture content. The specific heat of white and brown sesame seeds increased from 1062 to 3058 and from 906 to 2958 J/(kg·˚C) in the studied ranges of moisture and temperature.

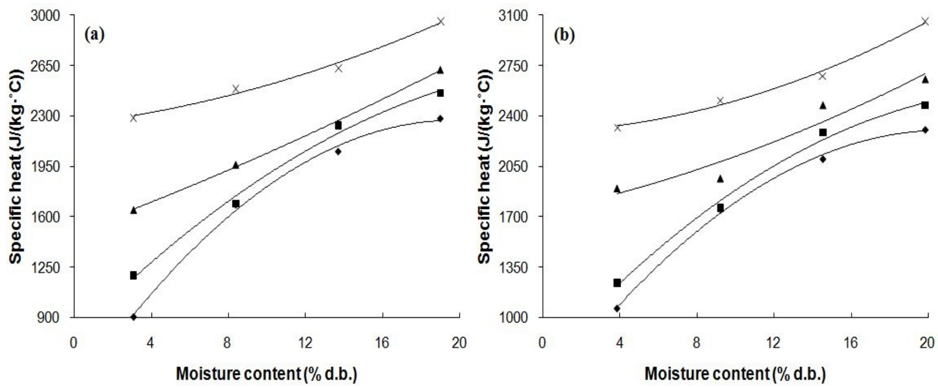

Figure 3. Specific heat of brown (a) and white (b) sesame seeds at differnet moisture content and temperature: (♦) 25˚C; (■) 40˚C; (▲) 55˚C; (×) 70˚C

The trend observed in this study was in agreement with previous findings of researchers. Dutta *et al*. (1988) showed that the specific heat of gram increased linearly from 1464 to 2904 J/(kg·˚C) with increase in temperature and moisture content in the range of 19-35˚C and 12.4-32.4% (d.b.), respectively. Singh and Goswami (2000) revealed that the specific heat of cumin seed depended on both moisture content and temperature. They reported that the specific heat increased as a second order polynomial from 1330 to 3090 J/(kg·˚C) with increasing of temperature and moisture content in the ranges of –70 to 50˚C and 1.8 to 20.5% (d.b.), respectively. Aviara and Haque (2001) investigated the effect of variation of moisture content (3.32-20.70% d.b.) and temperature (30-90˚C) on thermal properties of sheanut kernel and found that the specific heat values increased linearly with moisture content and temperature in the range of 1792-3172 J/(kg·˚C). Yang and Zhao (2001) stated that the specific heat of radish and alfalfa seeds increased from 290 to 479 and 333 to 593 J/(kg·˚C), respectively, in the moisture content ranges of 4.6 to 6.5% and 5 to 7.3% (d.b.), respectively, with increase in temperature from 30 to 80˚C. The specific heat capacity of borage seeds varied from 770 to 1990 J/(kg·˚C) at studied ranges of temperature (6 to 20˚C) and moisture content (1.2 to 30.3%, w.b.) (Yang *et al*., 2002). The specific heat of minor millet grains and flours increased from 1330 to 2400 J/(kg·˚C) with moisture content ranged from 10 to 30% (w.b.) (Subramanian and Viswanathan, 2003). Razavi and Taghizadeh (2007) showed that the specific heat of four varieties of Iranian pistachio nuts was a function of moisture content and temperature. They found that the specific heat increased from 419 to 2930 J/(kg·˚C) as a non-linear polynomial with increasing moisture content from 5 to 45% (w.b.) and temperature from 25 to 70˚C. The specific heat of whole and ground guna seed as a function of moisture content and temperature was determined by Aviara *et al.* (2008). They found that the specific heat of whole and ground seed increased from 1391.10 to 3020.13 J/(kg·˚C) and from 1459.14 to 3058.15 J/(kg·˚C), respectively, as the moisture content and temperature increased from 4.7 to 25.35% (d.b.) and 34 to 95˚C, respectively. Kocabiyik *et al.* (2009) found that the specific heat of pumpkin seed increased from 2530 to 3130 J/(kg·˚C) with increase in moisture content in the range of 5.32-24% (d.b.) at 85˚C. As well, the specific heat of red lentil seed increased linearly from 1080 to 2030 J/(kg·˚C) in the moisture range of 9.1-21.1% (w.b.) (Gharibzahedi *et al.*, 2013).

Nevertheless, the opposite trend was observed for roselle seeds (Bamgboye and Adejumo, 2010) where the specific heat capacity decreased linearly from 5630 to 4040 J/(kg·˚C) with increase in moisture content in the range of 8.8-19% (d.b.) at 80˚C. The pressure dependence of specific heat can be assumed to be negligible unless extremely high pressures are applied. Since most of the food processing operations are either at or in a close range of atmospheric pressure, the specific heat of food products is usually presented at constant pressures. Nonetheless, the specific heat of soybean oil, honey, cream cheese, water, 10% soy protein and 10% sucrose was reported by Nguyen (2009) as a function of pressure at 25˚C. The results indicated that specific heats decreased with increase in pressure. Effect of temperature, on the other hand, is negligible in the unfrozen temperature range while a dramatic effect is observed in the frozen temperature range (Mohsenin, 1980). In addition to the dependence of specific heat on pressure and temperature, it is worth noting that the weight of seeds greatly influence specific heats since this property is always higher for lighter seeds and lower for heavier seeds (Bamgboye and Adejumo, 2010).

The specific heat for white sesame seeds was always higher than that of brown sesame variety. This means that less energy is needed to heat brown sesame seeds to reach drying temperatures during the drying process (Nouri Jangi *et al.*, 2011). This behaviour can be attributed mainly to the different proximal compositions, especially moisture content (Sahin and Sumnu, 2006). Statistical analysis revealed that for both sesame varieties the moisture content and temperature had a significant effect ($p \leq 0.01$) on the specific heat values (Table 2). Thus, it can be said that the specific heat of the same variety can be changed as the moisture content and temperature changes. However, for both sesame seeds, comparing *F*-values of the moisture content and temperature showed that the effect of moisture content on specific heat was higher (high *F*-value) than the effect of temperature (low *F*-value). Increased specific heat with increasing moisture content might be due to the fact that water has a much higher specific heat than the other major constituents (lipid, protein, carbohydrate and ash) (Singh and Kotwaliwale, 2010; Bitra *et al.*, 2010). The increase in specific heat with increase in temperature within the study range was mainly due to the increasing number of excited degrees of free particles in the sesame seed (Chan *et al.*, 2012). Equations that express the relationship between the specific heat, temperature and moisture content of two type sesame seeds (white and brown) have been derived and reported in Table 1. The magnitudes of the regression coefficients in the equations confirmed the more effect of moisture content on specific heat than that of temperature. Alike polynomial equation had been reported for borage seed (Yang *et al*., 2002).

Table 1. Regression equations describing the relationship between the moisture content, temperature and thermal properties

Property	Variety	Equation	R^2	SEE
C_s	White	$C_s = -214.454+292.079M+16.248T-8.015M^2+0.289T^2-4.257MT+0.145TM^2$	0.98	87.33
	Brown	$C_s = -98.073+292.830M+9.492T-8.038M^2+0.343T^2-4.097MT+0.139TM^2$	0.99	64.44
α	White	$\alpha \times 10^{10} = 392.200+7.400M+1.802T+0.132MT$	0.96	2.27×10^{-9}
	Brown	$\alpha \times 10^{10} = 369.100+4.473M+1.708T+0.159MT$	0.95	2.43×10^{-9}
K	White	$k = -0.008+0.003M+0.001T+5.058\times10^{-6}MT$	0.95	0.0074
	Brown	$k = -0.011+0.003M+0.001T+9.667\times10^{-6}MT$	0.96	0.0068

C_s – specific heat; α – thermal diffusivity; k – thermal conductivity; M – moisture content; T – temperature; R^2 – coefficient of determination; SEE – standard error of estimate.

Thermal diffusivity

The variations of the thermal diffusivity of white and brown sesame seeds with moisture content at different temperature ranges are shown in Figure 4. The figure show that the thermal diffusivity of both white and brown sesame seeds increased with increase in temperature at a given moisture content and also with increase in moisture content at a given temperature. The average thermal diffusivity of white sesame varied between 4.66×10^{-8} and 8.59×10^{-8} m^2/s in the temperature range of 25-70˚C and moisture content range of 3.86-19.83% (d.b.). For the brown sesame seed it varied from 4.36×10^{-8} to 8.08×10^{-8} m^2/s in the moisture range of 3.07-18.99% (d.b.) and similar temperature range.

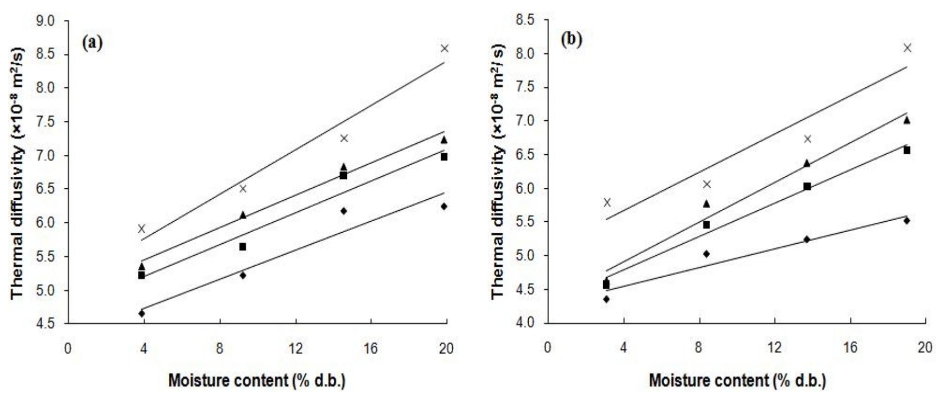

Figure 4. Thermal diffusivity of white (a) and brown (b) sesame seeds as a function of moisture content and temperature: (♦) 25˚C; (■) 40˚C; (▲) 55˚C; (×) 70˚C

This data is required to optimize energy consumption, efficient design of process equipment, to predict the location and magnitude of a temperature that denotes the heat content of the product at any time during a heating or cooling process, to maintain product quality, and to determine and control process parameters (Murakami, 2011). These results are supported by the findings of other researchers: Dutta *et al*. (1988) reported that the thermal diffusivity of gram varied from 9.46×10^{-8} to 16.35×10^{-8} m^2/s at the moisture content range of 12.5-26.5% (d.b.). Aviara and Haque (2001) showed that the thermal diffusivity of sheanut kernel varied from 6.94×10^{-8} to 8.1×10^{-8} m^2/s at temperature range of 74 to 76˚C and moisture content of 3.32 to 20.70% (d.b.). Yang and Zhao (2001) found that the thermal diffusivity of radish and alfalfa seeds increased from 25.13×10^{-8} to 34.47×10^{-8} and 27.14×10^{-8} to 29.73×10^{-8} m^2/s respectively, in the moisture content ranges of 4.6 to 6.5% and 5 to 7.3% (d.b.), respectively, as the temperature increased from 30 to 80˚C. Yang *et al*. (2002) also indicated the similar results for borage seed. They found that the thermal diffusivity increased from 2.32×10^{-7} to 3.18×10^{-7} m^2/s with increasing moisture content from 1.2 to 30.3% (w.b.) and temperature from 6 to 20˚C. Singh and Kotwaliwale (2010) calculated the thermal diffusivity from specific heat, thermal conductivity and bulk density for pigeonpea in the moisture range of 10 to 30% (w.b.) and the values ranged from 8.13×10^{-8} to 9.7×10^{-8} m^2/s. The thermal diffusivity of roselle seeds increased linearly from 4.274×10^{-4} to 4.477×10^{-4} m^2/s with increase of moisture content from 8.8 to 19% (d.b.) at 80˚C (Bamgboye and Adejumo, 2010). Results of work on peanut shells showed that by increasing moisture content from 3.5 to 28.7% (d.b.), thermal diffusivity increase from 5.9×10^{-7} to 6.7×10^{-7} m^2/s (Bitra *et al*., 2010).

However, these results were in contrast with the work done by other researchers. Hobani and Tolba (1995) experiments on three varieties of barley showed that when moisture increased from 10 to 30% (w.b.) thermal diffusivity changed from 8.76×10^{-4} to 6.03×10^{-4} m^2/h. Subramanian and Viswanathan (2003) studied the thermal traits of minor millet grains and flours in the moisture range from 10 to 30% (w.b.) and showed that thermal diffusivity decreased in the range of 0.82×10^{-3} to 0.55×10^{-3} m^2/h with increasing moisture content for both grains and flours. Thermal diffusivity of whole and ground guna seed decreased from 9.3×10^{-8} to 8.5×10^{-8} and from 3.0×10^{-7} to 8.5×10^{-8} m^2/s, respectively, with increase in moisture content (4.7-25.35%, d.b.) and temperature (24-36˚C) (Aviara *et al*., 2008). Kocabiyik *et al*. (2009) found that the thermal diffusivity of pumpkin seed decreased from 1.289×10^{-7} to 9.954×10^{-8} m^2/s with increase in moisture content in the range of 5.32-24% (d.b.), at 85˚C. Results of a study conducted by Bitra *et al*. (2010) revealed that the thermal diffusivity of peanut pods and kernels decreased from 2.8×10^{-7} to 2.3×10^{-7} and from 1.1×10^{-7} to 1.0×10^{-7} m^2/s, respectively, with increasing moisture content. Researchers' work on red lentil seed illustrated that increase in moisture from 9.1 to 21.1% (w.b.) will decrease thermal diffusivity from 2.15×10^{-7} to 1.65×10^{-7} m^2/s (Gharibzahedi *et al*., 2013).

Most foodstuffs have a complex and heterogeneous structure and are frequently anisotropic as well. Therefore, identifying of main reason of these behaviours is too complicated. Besides the temperature and moisture content, pressure also has a significant influence on thermal diffusivity (Mohsenin, 1980). The thermal diffusivity of soybean oil, honey, cream cheese, guacamole, water, tomato puree, 10% soy protein and 10% sucrose was reported by Nguyen (2009) as a function of pressure at 25˚C. The results indicated a slight increase in thermal diffusivity with increasing pressure. Amongst them, water and high moisture content foods had higher thermal diffusivity than that of other foods. The differences in thermal response of water, fats, and oils can be attributed to their molecular structure and phase transition characteristics (Mohsenin, 1980).

The experimental values of thermal diffusivity for white sesame seeds were constantly higher as compared to the other studied variety. This discrepancy can be attributed mainly to the different cell structure (chiefly fibre orientation) and chemical compositions of the seeds (specifically moisture content) (Mohsenin, 1980). The effect of moisture content and temperature was found to be significant on the thermal diffusivity of both varieties at a 99% confidence level (Table 2). This implies that the thermal diffusivity depends on the temperature and moisture content for these studied varieties. The analysis of variance table (Table 2) indicates a greater effect of the moisture content (high F-value) than that of the temperature on thermal diffusivity. The increasing of thermal diffusivity might be explained due to the fact that the bulk density decreases with increase in moisture content (Singh and Goswami, 2000). It should be noted that the thermal diffusivity of water is higher than that of other constituents of foodstuffs (fat, protein, carbohydrate and ash) (Sahin and Sumnu, 2006). Therefore, the variation trend of moisture content and thermal diffusivity is directly related to each other. The increment in thermal diffusivity with increase in temperature could be attributed to the increase in thermal conductivity of the contained water in the sample. The reason for this increase in thermal conductivity could be explained because of the fact that, when temperature increases, the number of collisions of water molecules per unit time increases and, consequently, the rate of heat flow increases in water (Rathore and Kapuno Jr, 2010). The regression equations of thermal diffusivity as a function of moisture content and temperature for each variety of sesame seed are presented in Table 1. The equations showed linear relationships between independent variables and the thermal diffusivity with very high correlation indicating that the equations are suitable for predicting the interactions between moisture content, temperature and thermal diffusivity of the sesame varieties. The magnitudes of the regression coefficients in the equations corroborated the stronger effect of moisture content on thermal diffusivity than that of temperature. Similar relationship had been reported for borage seed (Yang *et al*., 2002).

Thermal conductivity

The values of thermal conductivity were computed by equation (5) and its variations with moisture content and temperature for white and brown sesame seeds are shown in Figure 5. The values of thermal conductivity of white and brown sesame seeds increased with increase of moisture content and temperature from 0.031-0.149 and 0.023-0.135 W/(m·˚C), respectively, in the studied moisture content and temperature range.

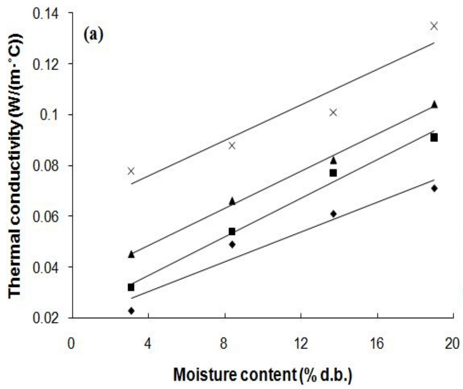

Figure 5. Variation of thermal conductivity of brown (a) and white (b) sesame seeds at different moisture content and temperature: (♦) 25˚C; (■) 40˚C; (▲) 55˚C; (×) 70˚C

These results are important to predict or control the heat flux in food during processing and may be useful for calculating energy demand for the design of equipment and optimization of thermal processing of sesame seeds (Gharibzahedi *et al*., 2013). Similar results of influence of moisture content and temperature on thermal conductivity have been reported for some agricultural produce. Dutta *et al*. (1988) reported that the thermal conductivity of the gram increased linearly from 0.144 to 0.247 W/(m·˚C) with increasing moisture and temperature in the ranges of 11.5 to 27.2% (d.b.) and 10 to 39˚C, respectively. Investigations of Hobani and Tolba (1995) demonstrated that the thermal conductivity of barley increased from 0.193 to 0.288 W/(m·˚C) with increase in moisture content in the range of 10 to 30% (w.b.). The thermal conductivity of cumin seed increased from 0.046 to 0.223 W/(m·˚C) with increase in temperature from -50 to 50˚C and moisture content from 1.8 to 20.5% (d.b.) and its variation with temperature and moisture was best represented by second order polynomial (Singh and Goswami, 2000). Fang *et al*. (2000) determined the thermal conductivity of four types of granular rice starches at temperatures of 20, 50 and 80˚C, and moisture contents of 4, 20 and 40% (w.b.). They found thermal conductivity increased significantly from 0.075 to 0.169 W/(m·˚C) with increase in temperature and moisture. The thermal conductivity of ground sheanut kernel in the moisture and temperature ranges of 3.32-20.70% (d.b.) and 74-76˚C, respectively, was found to lie between 0.094 and 0.129 W/(m·˚C) (Aviara and Haque, 2001). Investigations of Yang *et al*. (2002) showed that the thermal conductivity of borage seed increased from 0.11 to 0.28 W/(m·˚C) in the moisture range of 1.2 to 30.3% (w.b.) and the temperature range of 6 to 20˚C. The thermal conductivity of minor millet grains and flours increased from 0.026 to 0.223 W/(m·˚C) with moisture content in the range of 10-30% (w.b.). The thermal conductivity of flours was reported less than of grains (Subramanian and Viswanathan, 2003). Aviara *et al*. (2008) also indicated the similar results for guna seed. They found that the specific heat of whole and ground seed increased from 0.0711 to 0.1282 and from 0.125 to 0.223 W/(m·˚C), respectively, as the moisture content and temperature increased from 4.7 to 25.35% (d.b.) and 24 to 36˚C, respectively. Kocabiyik *et al*. (2009) observed an increase in thermal conductivity of pumpkin seed in the range of 0.113-0.135 W/(m·˚C) with increment in moisture content in the range of 5.32-24% (d.b.) at 85˚C. Singh and Kotwaliwale (2010) investigated the thermal properties of pigeonpea in the moisture range of 10 to 30% (w.b.). Their results revealed that thermal conductivity increased linearly in the range of 0.123 to 0.171 W/(m·˚C), with increasing moisture content. Gharibzahedi *et al*. (2013), by studying thermal properties of red lentil seed, reported a second-order polynomial relationship between their thermal conductivity and moisture content. Moreover, they indicated that the values of thermal conductivity increased from 0.191 to 0.241 W/(m·˚C) in the moisture content range of 9.1-21.1% (w.b.). On the other hand, an opposite trend between thermal conductivity and moisture content had been found for roselle seeds (Bamgboye and Adejumo, 2010) where the thermal conductivity decreased linearly from 1.56 to 1.22 W/(m·˚C) with increase in moisture content in the range of 8.8-19% (d.b.) at 80˚C.

It is clear that the lower thermal conductivity results in slowing the drying process (Nouri Jangi *et al*., 2011). Difference in thermal conductivity may be attributed to the variation in chemical composition, structure (porosity, pore size, shape, arrangement of different phases, such as air, water, solids) and processing conditions (temperature, pressure) (Gharibzahedi *et al*., 2013). Among these, the effect of operation pressure could be considerable. The thermal conductivity of apple juice, canola oil, clarified butter, honey and high fructose corn syrup was reported by Ramaswamy (2007) as a function of pressure. He found that the thermal conductivity of the test substances under pressure increased linearly with increasing pressure. When pressure increased from 0.1 to 700 MPa, thermal conductivity of water and water like substances increased from 0.61 to 0.82 W/(m·˚C), while for fatty foods such as canola oil the values changed from 0.20 to 0.29 W/(m·˚C). Studies of this researcher are not limited to liquid foods and by studying thermal properties of solid foods (carrots, cheddar cheese, guacamole and pork tenderloin), they showed that thermal conductivity of tested food materials increased linearly (R^2>0.95) with increasing pressure. Similar observation was also made by Nguyen (2009) who reported that thermal conductivity of 8 organic liquids increased with increase in pressure at 25˚C.

White sesame seeds had higher thermal conductivity values than that of brown sesame seeds. This is presumably a result of the lower moisture content of the brown sesame seed. The effect of moisture content and temperature on the thermal conductivity of the two sesame varieties was significant ($p \leq 0.01$). The analysis of variance table (Table 2) displayed that for both sesame varieties the effect of moisture content (high *F*-value) on the thermal conductivity was higher than the effect of temperature. The increased thermal conductivity with increasing moisture content might be due to higher thermal conductivity of water in comparison with the dry material of sample associated with air-filled pores (Bitra *et al*., 2010). The thermal conductivity of water is higher at a higher temperature (Rathore and Kapuno Jr, 2010). Thus, as the temperature increased, the thermal conductivity of sesame seeds increased. This phenomenon is beneficial to the food industry since processing time can be shortened greatly when higher processing temperature is employed (Fang *et al*., 2000). The best equations for predicting the thermal conductivity based on moisture content and temperature for each sesame seed variety and their coefficient of determination (R^2) are presented in Table 1. As it can be found, there is a linear relationship with very high correlation value between thermal conductivity and independent variables for two sesame seed varieties. Similar linear equation concerning predicted the thermal conductivity of borage seed was reported by Yang *et al*. (2002).

Table 2. Analysis of variance for effect of moisture content and temperature on specific heat, thermal diffusivity and thermal conductivity of sesame seed

			Specific heat		Thermal diffusivity		Thermal conductivity	
Variety	Source of Variation	Degree of freedom	Mean square	*F*-value	Mean square	*F*-value	Mean square	*F*-value
White	M	3	2310279.80	8345.07**	1.03×10^{-15}	240.57**	9.75×10^{-3}	1016.08**
	T	3	1653292.03	5971.93**	5.14×10^{-16}	119.66**	4.22×10^{-3}	440.08**
	M × T	9	78961.47	285.22**	1.84×10^{-17}	4.27**	1.18×10^{-4}	12.28**
	Error	32	276.84	–	4.30×10^{-18}	–	9.59×10^{-6}	–
	Total	47	268302.72	–	1.05×10^{-16}	–	9.21×10^{-4}	–
Brown	M	3	2498833.07	1350.15**	9.02×10^{-16}	61.49**	1.04×10^{-2}	1085.57**
	T	3	1637222.30	884.61**	3.39×10^{-16}	23.08**	4.53×10^{-4}	47.25**
	M × T	9	86845.83	46.92**	3.53×10^{-17}	2.40*	1.10×10^{-4}	11.47**
	Error	32	1850.78	–	1.47×10^{-17}	–	9.59×10^{-6}	–
	Total	47	281893.69	–	9.59×10^{-17}	–	7.21×10^{-4}	–

Asterisks indicate significance at **0.01 probability level and *0.05 probability level; M – moisture content; T – temperature.

4. Conclusions

The effect of moisture content and temperature (25-70˚C) on thermal properties such as specific heat, thermal diffusivity and thermal conductivity of two varieties of sesame seeds (namely; white and brown) was investigated. The moisture content ranged from 3.86 to 19.83% (d.b.) and from 3.07 to 18.99% (d.b.) for white and brown varieties, respectively. The specific heat, thermal diffusivity and thermal conductivity of both white and brown sesame seeds, were found to increase with increasing moisture content and temperature. The specific heat, thermal diffusivity and thermal conductivity of white sesame seeds were greater than those of brown sesame seeds in all situations. Both moisture content and temperature had significant ($p \leq 0.01$) effect on these three features for both studied varieties. The moisture content showed more effect than temperature on the studied thermal properties of both varieties.

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