Moisture dependent thermal properties of ground flaxseed (Linum usitatissimum)

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Abstract: The thermal properties of flours have been extensively used as engineering parameter in the design of processes and equipment to handle, transport, storage purpose and for protection of quality of technological process by processing to final products. The thermal properties of ground flaxseed (Linum usitatissimum) were investigated as a function of moisture content in the range of 4.82%-29.32% dry basis (d.b.) at six moisture levels, using a KD2 Pro Thermal Properties Analyzer. As the moisture content of ground flaxseed increased from 4.82 to 29.32 (% d.b.), the thermal conductivity, specific heat and thermal diffusivity increased from 0.122 to 0.184 W m-1 K-1, 2.94 to 5.64 kJ kg-1 K-1, and 6.42×10-8 to 8.11×10-8 m2/s, respectively. Ground flaxseed moisture content effect was statistically significant ($p<0.05$) on all properties and baseline data were generated for the development of necessary handling and processing equipment.

Keywords: ground flaxseed, thermal properties, bulk density, thermal conductivity, specific heat, thermal diffusivity

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1 Introduction

Flaxseed (*Linum usitatissimum*), also known as linseed, is a blue flowering crop and a member of family linaceae has been considered as an excellent functional food as a result of reports on its health promoting properties and its potential to reduce the risk of certain diseases (Oomah and Mazza, 2000). A flaxseed is smooth and oval with a pointed tip having a smooth surface and range in colour from brown to a golden yellow. The dimensions of flaxseed is found approximately 4.5-6.0 mm in length, 2.2-3.4 mm in width and 1.0-1.4 mm in thickness (Singh et al., 2014). Flaxseed is a remarkable source of alpha linolenic acid (ALA) which is an omega-3 fatty acid form the mass composition of polyunsaturated fatty acids and present about 50% of the total fatty acids (Daun and Przybyliski, 2000). ALA cannot be synthesized by the human body from any other substance, therefore it is considered as an essential fatty acid. The essential fatty acid requirements of the human body can be accomplished by the intake of flaxseed products (Morris, 2004). Further, 100 g of flaxseed provides 100% of the recommended daily allowance (RDA) for manganese and potassium, 57%-65% of the RDA of phosphorus and iron, and 13%-35% for zinc, calcium and copper while its recommended daily intake is 25 to 50 grams (Anon, 1994). In addition, flaxseed is a good source of high quality protein, fibers and phenolic compounds (Oomah, 2001). The demand for flaxseed based functional foods has been increased from the past couple of years because of the increased awareness of the nutritive and medicinal benefits it renders.

Thermal properties are frequently used in the engineering design calculations involving thermal processing such as pasteurization, sterilization, drying, heating, cooling, refrigeration, freezing, thawing, baking and frying in food processing, handling, and preservation operations. (Alagusundaram et al., 1991; Yang et al., 2002; Mahapatra et al., 2013). Moreover, comprehension of the thermal properties of flour is important in the analysis, prediction and control of various

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changes occurring in foods during heat transfer processes for equipment design as well as process associated with storage and processing. Thermal properties data are imperative both for developed foods and for novel products and processes. Moreover, during processing and preservation, thermal properties also cause significant effects on sensory quality of foods as well as consumption of energy (Fontana et al., 1999).

The main thermal properties of food products are thermal conductivity, specific heat and thermal diffusivity. Thermal conductivity of food materials is one of the important thermal properties used to estimate the rate of conductive heat transfer during processes, such as freezing, sterilization, drying, cooking, and frying. Moisture content plays a significant role due to the relative magnitude of conductivities of water in food (Cuevas and Cheryan, 1978). Thermal conductivity is the intrinsic property of a material and defined as the ratio of heat flux density to temperature gradient in a food material and characterizes the ability of material to convey heat. Specific heat is an important thermal property used in heat transfer and energy balance calculations (Kaletunç, 2007). Specific heat the property needed in the estimation of the amount of energy required to change the temperature of a food by one degree. It can be used to calculate the heat load imposed on the equipment by the loosing or gaining of heat. Thermal diffusivity is an important parameter that quantifies the ability of a food material to store thermal energy during heat transfer processes. Thermal diffusivity is defined as the ratio of thermal conductivity to specific heat and is the rate at which heat diffuses within a food material. It is the rate which thermal energy diffuses by conduction through a material (Rahman, 1996). Thermal diffusivity helps in estimating process time of heating, cooling, freezing and cooking (Fontana et al., 1999). It is also used in calculating the temperature change in storage bins because of fluctuations in external and internal temperature (Irtwange and Igbeka, 2003).

Many researchers have determined the thermal properties of various food powders and flours as a function of moisture content, such as Wallapapan and Sweat (1982) for soyflour, Taiwo et al. (1996) for ground cowpea, Božiková (2003) for corn and wheat flour, Mahapatra et al. (2011) for rice flour, Mahapatra et al. (2013) for cowpea flour, Subramanian and Viswanathan (2003) for millet flours, Aviara et al. (2008) for ground guna seed and Barnwal et al. (2014) for cryo-ground fenugreek powder.

A perusal of literature revealed that data on effects of moisture content on thermal conductivity, thermal diffusivity and specific heat of ground flaxseed is lacking. Therefore, the purpose of this study was to determine the influence of moisture content on the thermal properties of ground flaxseed.

2 Materials and methods

2.1 Materials

The flaxseeds used in this study were procured from local market of Jaipur, Rajasthan, India and were used for all the experiments in this study. The seeds were cleaned manually by the removal of all foreign matters such as stones, dirt and broken seeds. Further, the cleaned flaxseed was roasted until a nutty smell evolved. The roasting of flaxseed considerably reduces the cyanogenic glycosides content, thus making it fit for human consumption (Yang et al., 2004). Flaxseed were cleaned, graded and roasted in a cast-iron skillet and stir the seeds in the skillet constantly until the seeds turn a uniform dark brown. This should take from five to seven minutes. The roasted is poured in a bowl and stir until cool. Ultimately roasted flaxseed was grounded in a spice grinder. The initial moisture content of the ground flaxseed was determined by oven drying at 105±1℃ for 24 h. The initial moisture content of the ground flaxseeds was 4.82% dry basis (d.b.).

2.2 Preparation of samples

The evaluation of the effect of moisture content on the thermal properties of ground flaxseed was carried out at six moisture levels in the range of 4.28%-29.32% d.b. For the higher moisture contents (10.32%, 15.62%, 19.84%, 24.68%, and 29.32%) the ground flaxseed were conditioned by adding predetermined amounts of distilled water. The amount of water to be added (Q) to the samples of the desired moisture contents were prepared by adding the amount of pure analytical-grade water as calculated from the following equation ((Coşkun et al., 2005; Wang et al., 2007):

$$Q = \frac{W_i\,(M_f - M_i)}{(100 - M_f)} \qquad (1)$$

Where, Q is the mass of pure analytical-grade water to be added in kg, W_i is the initial mass of sample in kg, M_i is the initial moisture content of sample in % d.b., and M_f is the final (desired) moisture content of sample % d. b. The conditioned samples were packed separately in polythene bags and sealed tightly and stored in a refrigerator at a low temperature of at 5±1 ℃ in a refrigerator for seven days to enable the moisture to distribute uniformly (Singh et al., 2014). Before starting a test, the samples were taken out of the refrigerator and allowed to equilibrate to the room temperature for about two hours. Moisture content of the samples was determined in triplicates by oven drying at 105℃ for 24 h. Samples were removed from the drying oven and immediately placed in a desiccator for 30 min before weighing.

All the thermal properties of the ground flaxseeds were assessed at different moisture content with three replications. The following methods were used to determine some thermal properties of flaxseeds.

2.3 Methods

2.3.1 Thermal properties measurement

Thermal conductivity values of food materials have been determined by either the steady-state heat flow or transient heat flow method. The steady state heat flow method has a drawback that a long time is needed to reach steady-state conditions and the heat can be transferred by possible moisture migration due to temperature differences across the sample for a long time (Kazarian and Hall, 1965; Dutta et al., 1988; Alagusundaram et al., 1991). For this reason, the transient heat flow method has been preferred by many researchers to determine the thermal conductivity of food materials.

The transient heat flow is considered in an infinitive homogeneous medium heated by a line-heat source. The basic equation for the heat flow from heat-line source is as follows:

$$\frac{\partial T}{\partial t} = \alpha \left[\frac{\partial^2 T}{\partial t^2} + \frac{1}{r}\,\frac{\partial T}{\partial r}\right] \qquad (2)$$

Where, T is temperature at radius r in K, t time of heating sample in s, α thermal diffusivity in m^2/s, and r radial distance from the heat source in m. The solution of the differential equation is given by Hooper and Lepper (1950):

$$k = \frac{Q}{4\pi(T_2 - T_1)} \ln\left(\frac{t_2}{t_1}\right) \qquad (3)$$

Where, k is thermal conductivity in $Wm^{-1}K^{-1}$, Q heat input in W/m, and t time in s.

For the measurement of thermal properties, KD2 Pro Thermal Properties Analyzer (Decagon Devices Inc.), equipment was used to apply the transient line heat source method. It consists of a handheld microcontroller and sensor needles. The KD2's sensor needle contains both a heating element and a thermistor measuring the thermal conductivity, thermal diffusivity and specific heat (heat capacity) concurrently. Five to six min gap was provided between each reading. All the thermal properties were determined at the moisture contents of 4.82%, 10.32%, 15.62%, 19.84%, 24.68%, and 29.32% (d.b.) at room temperature of 24 (±1) ℃.

2.3.2 Statistical analysis

The experimental design for measuring thermal properties at six moisture contents by three replications within each test were conducted for ground flaxseed. The relationships existing between ground flaxseed thermal properties and their moisture content and density were established using the analysis of variance (ANOVA) and Duncan Multiple Range Test (DMRT) in SPSS 13.0 for Windows. Least Significant Difference (LSD) among means was calculated at 5% significant level ($p < 0.05$).

3 Results and discussion

3.1 Thermal conductivity

The thermal conductivity of the ground flaxseed was found to be increased from 0.122 to 0.184 W m^{-1} K^{-1}, as the moisture content increased from 4.82% to 29.32% (d.b.) and is presented in Figure 1. The mean thermal conductivity values measured at six moisture content levels were significantly different ($p<0.05$). Consequently, it indicates that heat transfer rate in ground flaxseed is better when wet than when they are dried. The relationship is expressed in a linear equation (Table 1). This means that for every unit increase in ground flaxseed moisture content, there will be a corresponding unit increase in its thermal conductivity. The increased thermal conductivity of ground flaxseed with increasing moisture content might be due to higher thermal conductivity of water compared to the dry material of sample associated with air-filled pores. The relationship existing between thermal conductivity and ground flaxseed moisture content can be expressed using the following equations:

$$k = 0.002\,(M_c) + 0.113 \quad (R^2 = 0.933) \qquad (4)$$

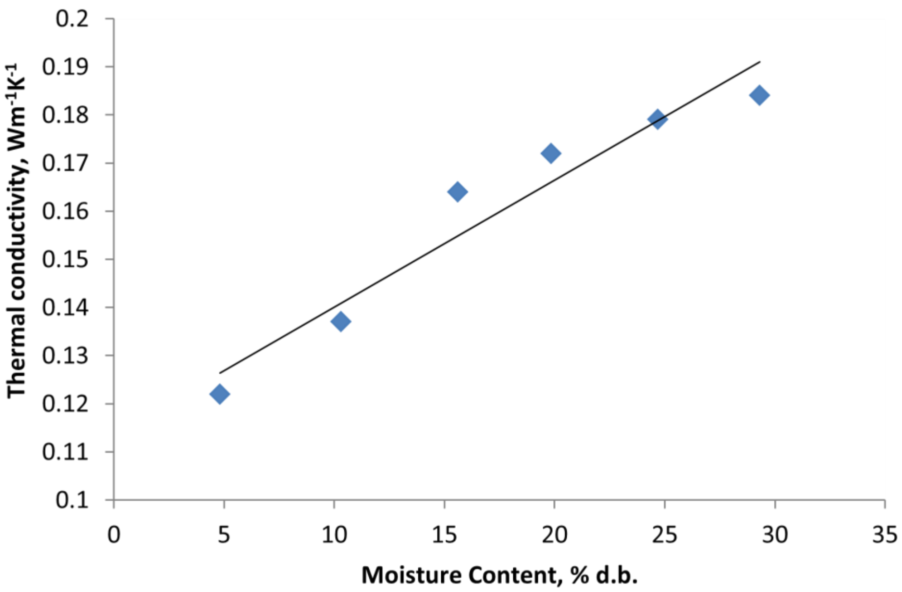

Figure 1 Thermal conductivity of ground flaxseed as a function of moisture content, % d.b.

Table 1 Equations representing relationship between moisture content of ground flaxseed and thermal properties

Equations	R^2	Equation No.
$k = 0.002(M_c) + 0.113$	0.933	(4)
$C_s = -0.004(M_c)^2 + 0.2423\,(M_c) + 1.898$	0.944	(5)
$\alpha = 0.007(M_c)^2 - 0.168(M_c) + 6.919$	0.930	(6)

Note: R^2 = Coefficient of determination; M_c = Moisture content (% d.b.)

Similar trend was observed in the thermal conductivity of soyflour (Wallapapan and Sweat, 1982), ground cowpea (Taiwo et al., 1996), corn and wheat flour Božiková (2003), rice flour (Mahapatra et al., 2011) and cowpea flour (Mahapatra et al., 2013).

3.2 Specific heat

The specific heat capacity of ground flaxseed (Figure 2) was found to be increase from 2.94 to 5.64 kJ $kg^{-1}K^{-1}$ with an increase in ground flaxseed moisture content from 4.82 to 29.32 (% d.b.) and was statistically significant (Table 2). Increased specific heat with increasing moisture content is due to the high specific heat of water compared to the dry material, and the water occupying the air-filled pores faster at lower moisture contents. Based on the experimental data, the specific heat of ground flaxseed, as a function of moisture content, can be expressed using the following regression equations in form of a second order polynomial equation:

$$C_s = -0.0041(M_c)^2 + 0.2423\,(M_c) + 1.898 \quad (R^2 = 0.944) \qquad (5)$$

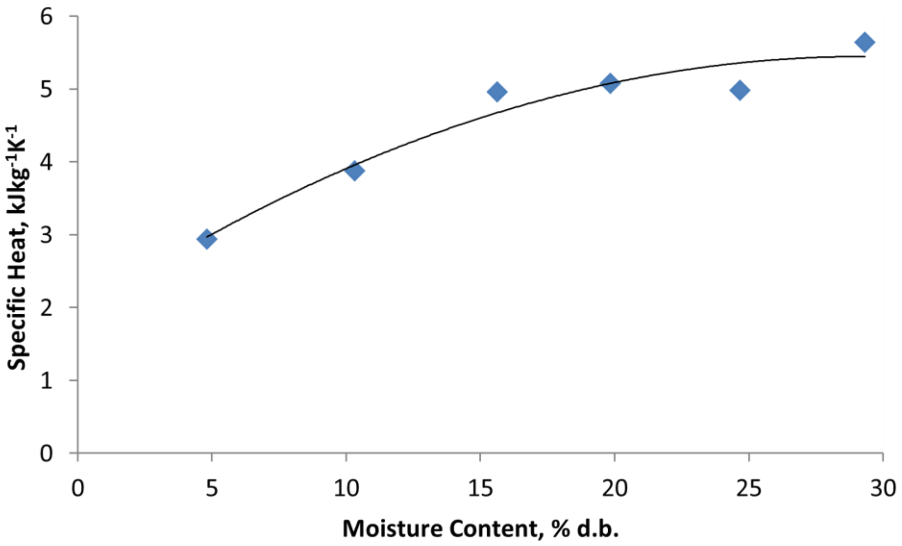

Figure 2 Specific heat of ground flaxseed as a function of moisture content, % d.b.

Table 2 Effect of moisture content on thermal properties of ground flaxseed

Moisture content, % d.b.	Thermal conductivity, W m^{-1} K^{-1}	Specific heat, kJ $kg^{-1}K^{-1}$	Thermal diffusivity, X 10^{-8} m^2s^{-1})
4.82	0.122a ±0.01	2.94a ±0.48	6.42a ±0.24
10.32	0.137ab ±0.02	3.88b ±0.47	5.80a ±1.06
15.62	0.164b ±0.01	4.96c ±0.68	5.89a ±0.96
19.84	0.172a ±0.02	5.08c ±0.36	6.58a ±0.71
24.68	0.179b ±0.01	4.98c ±0.38	7.67ab ±0.29
29.32	0.184b ±0.01	5.64c ±0.44	8.11b ±0.32

Note: Values in the same column followed by different letters (a-c) are significant (P<0.05).

Similar trend was observed in the specific heat of millet flours (Subramanian and Viswanathan, 2003), ground guna seed (Aviara et al., 2008), cowpea flour (Mahapatra et al., 2013) and cryo-ground fenugreek powder (Barnwal et al., 2014).

3.3 Thermal diffusivity

The thermal diffusivity of ground flaxseed increased from 6.42×10^{-8} to 8.11×10^{-8} m^2/s as the moisture content increased from 4.82% to 29.32% (d.b.). The mean thermal diffusivity values measured at six moisture content levels were significantly different (p<0.05) except between 4.82% and 10.32 (% d.b.). The relationship between moisture content and thermal diffusivity of ground flaxseed shown in Figure 3 is a polynomial of the second order equation (Table 1). The reason behind the increase of thermal diffusivity might be due to the increase of moisture content of ground flaxseed, the pores and capillaries of the ground flaxseed which was initially filled with air was gradually displaced by absorbed water. The heat was released by water adsorption in the ground flaxseed and as a result the thermal diffusivity increased (Kostaropoulos and Saravacos, 1997). The relationship between moisture content and thermal diffusivity was expressed as a second order polynomial equation:

$$\alpha = 0.007(M_c)^2 - 0.168(M_c) + 6.919 \quad (R^2 = 0.930) \quad (6)$$

Similar pattern was observed for corn and wheat flour (Božiková, 2003), for cowpea flour (Mahapatra et al. 2013), millet flour (Subramanian and Viswanathan, 2003) and cryo-ground fenugreek powder (Barnwal et al., 2014). In contrast, Mahapatra et al. (2011) reported that thermal diffusivity of rice flour decreased with the increase in moisture content.

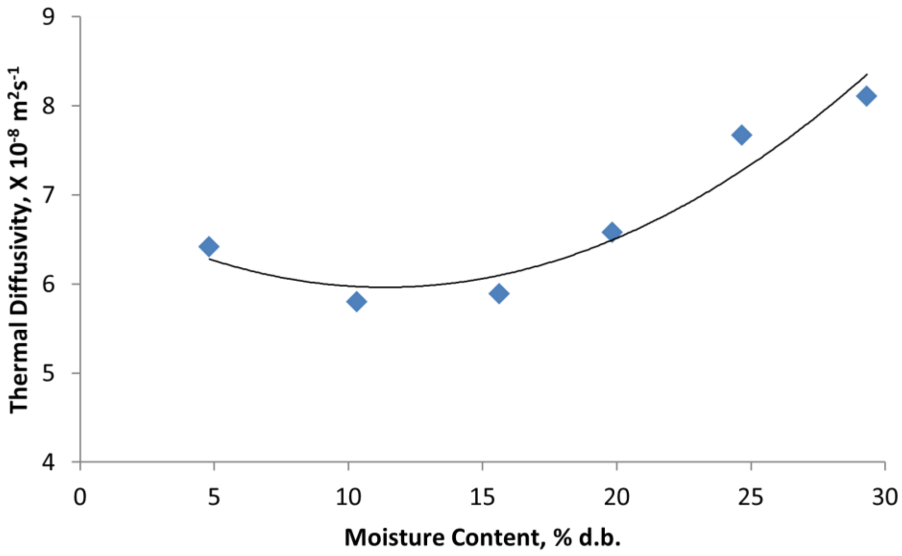

Figure 3 Thermal diffusivity of ground flaxseed as a function of moisture content, % d.b.

4 Conclusions

In this study, the effect of moisture content on thermal conductivity, specific heat and thermal diffusivity of ground flaxseed was investigated. The thermal properties of ground flaxseed determined as a function of moisture content varied significantly with increased moisture content. Thermal conductivity, thermal diffusivity and specific heat increased with an increase in moisture content. It can be concluded from this study that moisture content has a significant effect on the thermal properties of ground flaxseed measured in this study.

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