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Thermal Conductivity of Sunflower Seed as a Function of Moisture Content and Bulk Density

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Abstract: The thermal conductivity of sunflower seed was determined as a function of moisture content, bulk density and temperature which varies from 0.1 to 30.48% (w.b.) and 437.14 to 352.5 kg/m^3 and 22 to 46°C, respectively. The slope of the linear portion (ΔT versus ln(t)) method was used to analyze the line source heating data for thermal conductivity determination. Bulk density of sunflower seeds followed a multiply relationship with moisture content. Thermal conductivity increased with increasing moisture content and decreasing bulk density and the values were in the range between 0.1854 to 0.3047 W/mK. However, the effect of moisture content on increasing the thermal conductivity was more than that of bulk density. Regression equations were established which could be used to reasonably estimate the values of the thermal conductivity as a function of moisture content and bulk density.

Key words: Thermal conductivity · Sunflower seed · Moisture content · Bulk density · Temperature · Line heat source

INTRODUCTION

The transient heat conduction during material is an important heat transfer mechanism in materials. Also, in the food industry, thermal properties are important parameters to determine to design equipment or its parts and, in computer simulation, to analyze, optimize and control of the temperature during the elaboration, storage, transport and commercialization of foods is very important. One of the most important heat properties for agricultural products is thermal conductivity. This value shows heat transfer intensity in unit area from unit thickness in unit time to change solid temperature 1°C. The design and control of equipment are difficult due to the lack of information on the behavior of the thermo physical properties with composition and temperature. Equipment size is usually overestimated to compensate for this lack of information, leading to a non-ideal design with cost implications as well as inferior quality of the product.

These thermal controls can only be put in practice by the precise knowledge of the thermo physical characteristics of the food stuffs. These works are realized to foresee how the heat and mass transfers occur in the products, with the final objective of the optimization of these processes. There are numerous methods to measure the thermal properties proposed in the specialized literature. The heated probe method is based on the line heat source, a non-steady state method. It is the most widely used method because of its simplicity, rapid measurement and suitability for small food samples. Also, it eliminates moisture loss and moisture migration within the material.

Various researchers [1-6] reported that the major factors influencing thermal properties of materials are: temperature, water content, fat, state of pressure and density. Materials with lower porosity have lower thermal conductivity. Also, heat conductivity of solids increases with moisture content [1,3,4,7].

The objectives of this research were to determine the thermal conductivity in order to design or select an appropriate dryer or a thermal treatment unit. The effects of sunflower seed moisture content and bulk density on thermal conductivity were also determined.

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MATERIALS AND METHODS

Preparation of Samples: The initial moisture content of sample was determined by using a standard oven method at 103±1°C for 24 h [8] and was found to be, 5.02% (wet basis). Four levels of moisture contents of sample were selected as 0.1, 5.02, 14.31 and 30.48% (wet basis). To obtain samples with higher moisture contents, a calculated quantity of distilled water was added; the samples were then placed in sealed plastic bags and kept at 277 K in the refrigerator for at least a week to enable the moisture to distribute uniformly throughout the sample. Before starting a test, the required quantity of seeds was taken out of the refrigerator and allowed to warm up to room temperature [9]. The quantity of distilled water was calculated from the following equation [10]:

$$W_2 = W_1 \frac{M_1 - M_2}{100 - M_1} \quad (1)$$

Where, W_2 is the mass of distilled water added (kg), W_1 is the initial sample mass (kg), M_1 is the initial moisture content of sample (% w.b.) and M_2, desired moisture content of sample (% w.b.). The weights of samples were measured by a digital balance (GF-600, A & D, JAPAN) with an accuracy of 0.001 g.

Before each experiment, the required samples were then taken out from the oven and kept sealed in an ambient environment for about 30 min to equilibrate the water and temperature throughout the sample. The samples were then are kept in the ambient environment in sealed conditions so there is no chance of change of moisture content.

Experimental Apparatus and Procedure: The apparatus (Fig. 1) consisted of a Pyrex cylinder 83 mm in height and 29 mm in inner diameter, with a removable rubber top and bottom cover. The resistance of the heating wire was 30.37 Ω/m with a diameter of 0.4 mm threaded through a stainless steel needle (0.5 mm diameter and 71 mm length) and connected to a AC power source, 7.5 V.

Temperature rise was measured by thermocouple type K, inserted approximately 0.8 mm from the heating wire (i.e. the heating wire and the thermocouple was held together and separated apart for around 0.8 mm by the glue). The multi-meters (ET-2230, Minipa, China) were interfaced to a computer by a RS-232 cable and the current and temperature were recorded on-line every 1s throughout heating using software for the multi-meter.

The theory of the line-heat source probe method is based on several assumptions;

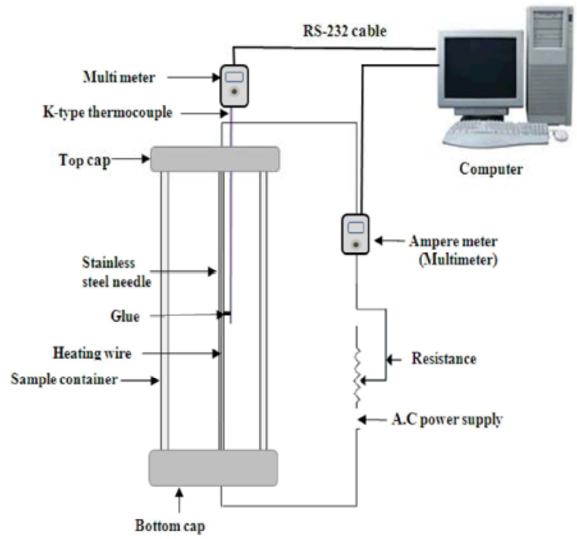

Fig. 1: Schematic of the apparatus used for measuring thermal conductivity

- A line-heat source (no mass and no volume) is placed in an infinite medium of a uniform initial temperature distribution with constant thermo-physical properties.
- At a zero time, heat is generated along a line at a constant rate.

For a long cylinder wire with constant heat generation in an infinite surrounding medium, the governing equation defining the temperature distribution is given by:

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} = \frac{1}{\alpha}\frac{\partial T}{\partial r} \quad (2)$$

The heat transfer equation applicable for the line heat source method is the Fourier equation. The solution to the Fourier equation for the line heat source method has been given by several researchers, including Carslaw and Jaeger [11]. This solution for the change in temperature at a point close to the line heat source as a function of time can be written as:

$$\Delta T = \frac{Q}{4\pi k}\left[\ln(t) + \ln\left(\frac{4\alpha}{r^2 e^{0.5772}}\right)\right] \quad (4)$$

Where, ΔT is the temperature rise at a distance r from the line-heat source probe (°C); t is the time (s), Q is the heating power/unit of probe length (W/m); k is thermal conductivity (W/m.K); α is thermal diffusivity (m^2/s); r is the distance from central axis probe (m).

Equation (8) shows a linear relationship between ΔT and ln(t) with the slope S=Q/4πk. The slope S can be obtained from the experimental data of ΔT versus ln(t) by linear regression and the thermal conductivity can then be calculated from the linear slope S:

$$k = \frac{Q}{4\pi S} \quad (4)$$

Since Q = I^{2}R, the above equation can be rearranged as:

$$k = \frac{I^2R}{4\pi S} \quad (5)$$

Where, I is the electric current; R is the electric resistance per unit length (Ω/m).

Owing to non-ideal conditions in reality, such as nonzero mass and volume of the hot wire, heterogeneous and anisotropic properties of biological materials, finite sample size and axial heat flow, ΔT versus ln(t) does not always follow a linear relationship. Among the published methods for thermal conductivity measurement, the slope of the linear portion of the relationship between temperature rise and the logarithm of time has so far been the most accurate and rapid method.

Data Analyses: The results were reported as an average of three replicates. Analysis of variance of the two factors and interactions were applied to the different sets of data. Least significant differences were calculated by the Fisher test (α=0.05). The analysis was performed using a standard statistical program.

RESULTS AND DISCUSSIONS

Temperature rise increased rapidly with time during initial stages of heating but later on it increased at reduced rate (Fig. 2). The initial stages of heating showing higher rates of temperature rise were due to the slow absorption of thermal energy by the samples.

The reduced rate of rise in temperature during later stages might be due to the rapid transfer of thermal energy through heat conduction from the inner most layers of the samples, adjacent to line heat source, to outer layers. The increasing trend might have continued after the end of the experiment at 5.5 to 7 min. The uniform rising trend in temperature clearly indicated transient-state (i.e. unsteady-state) heat transfer from the line heat source.

Table 1: Bulk density of sunflower seeds

Moisture content (% w.b.)	Bulk density (kg/m^3)	SD
0.10	437.14	±5.03
5.02	403.19	±11.44
14.31	360.25	±6.82
30.48	352.05	±8.27

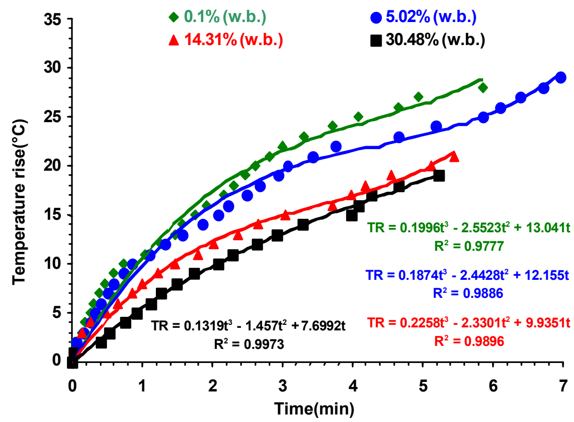

Fig. 2: Variation of temperature rise with time heating

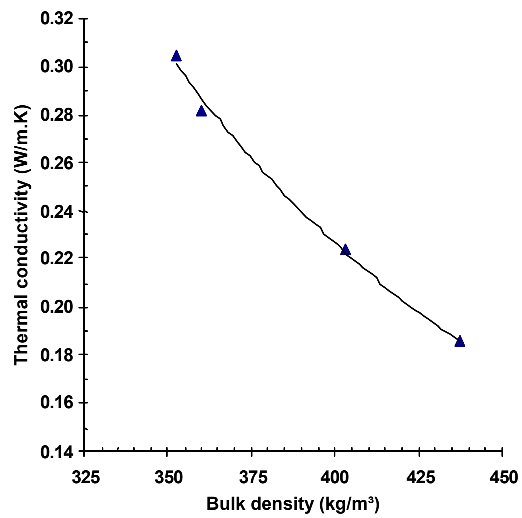

Fig. 3: Variation of thermal conductivity of sunflower seed with bulk density

The resultant bulk density data were shown in Table 1. The decrease in bulk density of sunflower seed with increase in moisture content may have been caused by the decrease of particle density due to the absorption of moisture by the sample particles. Similar trend was observed in the bulk density of sunflower seed by Seifi and Alimardani [12]; Gupta and Das [8]; Isik and Izli [13]; and Santalla [14].

The bulk density of sunflower seeds can be approximated by a second-order polynomial (parabolic) as given below:

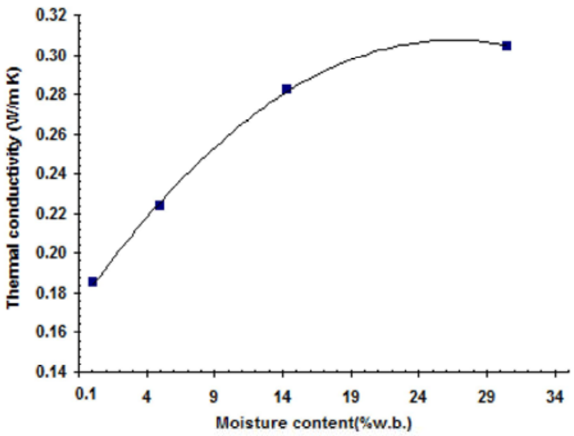

Fig. 4: Variation of thermal conductivity of sunflower seed with moisture content

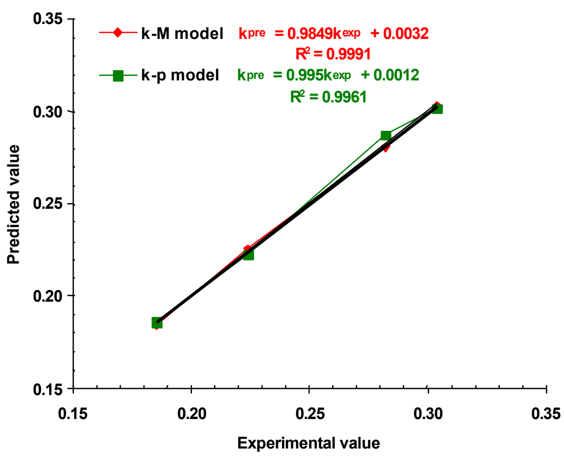

Fig. 5: Comparison of thermal conductivities determined by experimentation and prediction using the moisture content and bulk density

$$\rho = 0.1622M^2 - 7.7487M + 437.94 \qquad R^2 = 0.999 \qquad (6)$$

Where, ρ is th bulk density (kg/m^3) and M is the moisture content (% w.b.).

Statistical analysis indicated that moisture content and bulk density had significant effect on the thermal conductivity values at a 5% significance level. The thermal conductivity of sunflower seed was found to increase from 0.1854 to 0.3047 W/m.K, as the moisture content increased (Fig.3). The increased thermal conductivity 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. Similar trend was observed in the thermal conductivity of cumin seed [15], sheanut kernel [16], borage seed [3], rough rice [17], millet grains [18], Berberis Fruit [19] and safflower [20]. From Fig.4, it can be seen that the thermal conductivity increased with decrease in the bulk density of sunflower seed in the above moisture range. Such variation has been reported for the thermal conductivity of sheanut kernel [16].

The relationship existing between thermal conductivity and seed moisture content and bulk density can be expressed using the following equations:

$$k = -1.8\times10^{-4} M^2 + 0.0094M + 0.1834 R^2 = 0.9993 \qquad (7)$$
$$k = 1.56114\times10^5 \rho^{-2.2436} R^2 = 0.9972 \qquad (8)$$

Comparing measured values of the moisture content and bulk density showed that the effect of moisture content on the thermal conductivity was higher than the effect of bulk density. This may be due to the fact that the thermal conductivity of water ranges from 0.6106 to 0.6372 W/m.K at temperatures of 26.5±45.0°C [21] which is much higher than that of air filled in pores following reduction in moisture. Fig. 5 compare experimental data with those predicted with the two models for sunflower seed at different conditions. The prediction using the model showed thermal conductivity values banded along the straight line, which showed the suitability of these models in describing thermal conductivity of samples.

CONCLUSIONS

Results of this investigation clearly showed significant variation in thermal conductivity of sunflower seeds with changing moisture content and bulk density. The developed models can be used to predict the thermal conductivity satisfactorily within the range of input variables studied. The thermal conductivity of sunflower seed increased from 0.1854 to 0.3047 W/mK with increasing moisture content from 0.1 to 30.43% (w.b.) and decreasing bulk density from 437.14 to 352.5 kg/m^3.

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