Thermal conductivity of safflower (Carthamus tinctorius L.) seeds

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Abstract

The thermal conductivity of agricultural seeds has been used as engineering parameter in the design of processes and machines for drying, storing, aeration and refrigeration. The thermal conductivity of safflower seeds was determined and its changes with moisture content, bulk density and cultivar investigated. The thermal conductivity values of cv. Remzibey-05 increased from 0.105 to 0.132 W m⁻¹ K⁻¹ and from 0.108 to 0.137 W m⁻¹ K⁻¹ for low and high (loose and dense) bulk densities, respectively, as the moisture content increased from 5.79 to 20.38% db. Likewise, the thermal conductivity values of cv. Dinçer increased from 0.106 to 0.137 W m⁻¹ K⁻¹ and from 0.110 to 0.140 W m⁻¹ K⁻¹ for low and high bulk densities, respectively in the moisture range of 5.07 to 20.30% db. The thermal conductivity values obtained with the high bulk density was higher than those obtained with the low bulk density for both cultivars. The thermal conductivity value of cv. Dinçer seeds was lower than that of cv. Remzibey-05 seeds.

Additional key words: bulk density; moisture content.

Introduction

Safflower (Carthamus tinctorius L.) is an annual oilseed crop. Its production has recently been increased due to its seed oil (Baümler et al., 2006). Turkey is the fifth country in the production of safflower in the year 2009 after India, USA, Argentina and Kazakhstan. The production of safflower rose in Turkey from 18 t in the year 2000 to 20,076 t in 2009 and from 624,610 t in the year 2000 to 653,791 t in 2009 in the world (FAO, 2011; http://faostat.fao.org).

Thermal properties of food and agricultural materials are important engineering parameters in the design of processes, equipments, and machines needed in drying, storing, aeration and refrigeration. One of such properties is the thermal conductivity.

A number of researchers have determined the thermal conductivity for several grains, seeds, and kernels such as durum wheat (Triticum durum Desf.) (Tavman and Tavman, 1998), soybean [Glycine max (L.) Merr.] (Munde, 1998), cumin (Cuminum cyminum Linn.) seed (Singh and Goswami, 2000), sheanut (Butyrospermum paradoxum) kernel (Aviara and Haque, 2001), borage (Borago officinalis) seed (Yang et al., 2002), minor millet (Sestaria italica, Panicum miliare, Panicum miliaceum, Paspalum sorobiculatum, Eleusine coraca-
_na, Echinochola colona_ grains (Subramanian and Viswanathan, 2003), cereal grains (Kayişoğlu et al., 2004), guna (_Citrus colocynthis_ seed (Aviara et al., 2008), black cumin (_Nigella sativa_ L.) seed (Almahasneh et al., 2008), coriander (_Coriandrum sativum_ L.) and anise (_Pimpinella anisum_ L.) seeds (Hacikuru and Kocabiyik, 2008), chickpea (_Cicer arietinum_ L.) (Singh et al., 2008), pumpkin (_Cucurbita pepo_ L.) seeds (Kocabiyik et al., 2009), and roselle (_Hibiscus sabdariffa_ L.) seeds (Bamgboye and Adejumo, 2010). Data on the thermal conductivity of safflower does not appear to be available in the literature. The objective of this study was to determine the thermal conductivity of safflower seeds as affected by moisture content, bulk density and cultivar.

**Material and methods**

**Theoretical background**

Thermal conductivity values of agricultural materials have been determined by either the steady-state heat flow or transient heat flow method. The steady-state heat flow method has two disadvantages: (i) a long time is needed to reach steady-state conditions and (ii) 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 agricultural 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:

\[
\frac{\partial T}{\partial t} = \alpha \left[ \frac{\partial^2 T}{\partial t^2} + \frac{1}{r} \frac{\partial T}{\partial r} \right] \tag{1}
\]

where \(T\) is temperature at radius \(r\) in K, \(t\) time of heating sample in s, \(\alpha\) thermal diffusivity in m\(^2\) s\(^{-1}\), and \(r\) radial distance from the heat source in m. The solution of the differential equation is given by Hooper and Lepper (1950):

\[
k = \frac{Q}{4\pi(T_f - T_i)} \ln(t_f/t_i) \tag{2}
\]

where \(k\) is thermal conductivity in W m\(^{-1}\) K\(^{-1}\), \(Q\) heat input in W m\(^{-2}\), and \(t\) time in s.

The heat input is expressed as follows:

\[
Q = VI/L \tag{3}
\]

where \(V\) is voltage in V, \(I\) current in A, and \(L\) length of heater wire in m.

**Sample preparation**

Two safflower cultivars, ‘Remzibey-05’ and ‘Dinçer’ were used in the experiments. They were supplied from the Southeast Anatolia Project Soil-Water Resources and Agricultural Research Institute, Sanlıurfa, Turkey. The seeds were cleaned manually to remove dust and foreign materials. The thermal conductivity measurements were conducted at four different moisture levels (Table 1). The initial moisture content accepted as low moisture level of the grain and was determined by keeping the sample in the oven at 105 ± 1°C for 24 h (Suthar and Das, 1996; Altuntafl and Yıldız, 2007). The desired moisture contents for higher levels were obtained by adding the distilled water of mass calculated by the following equation:

\[
W = \frac{W(M_f - M_i)}{(100 - M_f)} \tag{4}
\]

where \(W\) is mass of water added to sample in kg, \(W\) sample mass in kg, \(M_i\) initial moisture content of sample in % d.b. and \(M_f\) final moisture content of sample

**Table 1.** Moisture content levels and bulk densities of the safflower cultivars

<table>
<thead>
<tr>
<th>Safflower cultivar</th>
<th>Moisture content (% db)</th>
<th>Bulk density (kg m(^{-3}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Remzibey-05</td>
<td>5.79</td>
<td>536.4</td>
</tr>
<tr>
<td></td>
<td>9.66</td>
<td>526.8</td>
</tr>
<tr>
<td></td>
<td>14.24</td>
<td>528.5</td>
</tr>
<tr>
<td></td>
<td>20.38</td>
<td>531.0</td>
</tr>
<tr>
<td>Dinçer</td>
<td>5.07</td>
<td>577.5</td>
</tr>
<tr>
<td></td>
<td>9.67</td>
<td>566.1</td>
</tr>
<tr>
<td></td>
<td>15.45</td>
<td>571.7</td>
</tr>
<tr>
<td></td>
<td>20.30</td>
<td>572.7</td>
</tr>
</tbody>
</table>

(db: dry basis.)
in % d.b. The prepared sample was sealed in separate bags and kept in a refrigerator at 5°C for 7 days to enable the moisture to diffuse uniformly throughout the sample. The actual values of moisture content of the prepared samples were also determined by keeping the sample in the oven at 105 ± 1°C for 24 h (Suthar and Das, 1996; Altuntaş and Yıldız, 2007). Just before starting a test, the required amount of seed was taken out of the refrigerator and was allowed to equilibrate at room temperature for at least 24 h (Dutta et al., 1988; Alagusundaram et al., 1991).

**Measurement of thermal conductivity**

In this study the thermal conductivity values of the seed were determined by transient heat flow using line-heat source principle. A thermal conductivity probe was developed and used for measuring thermal conductivity. The measurement system consists of three components (Fig. 1a): (i) a probe including a temperature sensor and a heater wire, (ii) a DC power supply for supplying the wire, and (iii) a computer equipped with DAS for recording the temperature values. A thermal conductivity probe was developed as shown in Figure 1b. The probe was made of stainless steel tube with 6 mm outer diameter, 4 mm inside diameter, and 240 mm length which gave a length to diameter ratio of 40 to eliminate the error due to finite size of the heating element. As cited by Tavman and Tavman (1998), Blackwell (1956) reported that when the ratio of length to diameter of the probe is 30 or more the error due to finite length is negligible. A nickel-chrome heating wire with 0.2 mm diameter and 24 cm length is placed inside the tube and connected to the DC power supply. A diode (1N4148A) was used as a temperature sensor. The temperature sensor was positioned in the midpoint of the tube at contact with the inner surface of the tube with the aid of a steel spiral spring. The space remaining in the tube was carefully filled with Al₂O₃ powder for increasing heat transfer within the probe. The temperature sensor was calibrated from 4 to 81°C using a thermocouple equipped with a temperature controller model REX-P250. For thermal conductivity determinations, the probe was inserted longitudinally into the center of the cylindrical holder filled with prepared sample. The cylindrical sample holder made of fiberglass had 25 cm height and 15 cm inside diameter. The sample was equilibrated at room temperature. When the sample temperature reached the equilibrium the heater wire was energized by the regulated DC power supply with a 0-30 V and 0-3 A (Model GPS-3030DD Good Will) to make heat transfer at radial direction from the probe into the surrounding sample. The temperature rise was measured by the temperature sensor in the probe and recorded at every minute during a period of 10 minutes. A constant DC power source of 5 V and 520 mA producing 10.83 W m⁻¹ was found suitable to give a temperature rise of 21°C from room temperature of 20°C to 41°C in about 10 minutes. The signals sensed by the temperature sensor were transmitted to computer through a PCLD 770 signal conditioning board and a DACpad-71/B data acquisition module. The temperature values versus the elapsed time curves were obtained on the monitor of PC.

From this experimental data, a thermogram plotting the temperature values versus the natural logarithm (ln) of elapsed time was obtained. A typical thermogram showing the linearity of temperature versus In
time is given in Figure 2. The thermal conductivity was calculated using the Eq. [2] for the linear portion of the thermogram. The Eq. [2] can be expressed as follows:

$$k = \frac{Q}{4\pi} \frac{1}{S}$$  \[5\]

where $S = \ln(t_2 / t_1) / (T_2 - T_1)$ is slope of the straight line portion of the plot of $T$ versus $\ln(t)$ shown in Figure 2. On the other hand, the Eq. [2] has been used by many researchers (Kazarian and Hall, 1965; Sweat, 1974; Morita and Singh, 1979; Tavman and Tavman, 1998; Shrivastava and Datta, 1999; Tansakul and Chaisawang, 2006; Tansakul and Lumyong, 2008) for determining the values of thermal conductivities of various agricultural materials.

**Bulk density**

In order to provide low (loose) bulk density the seeds were poured into the holder through a funnel without tapping. In order to provide high (dense) bulk density the seeds were poured into the holder with 12 gentle taps around the holder and the holder was dropped three times at 10 cm high at each one-third of the container filling (Chang, 1986). The filled sample was weighed and the bulk density of the sample in the holder was calculated by ratio of mass to volume. The bulk densities studied for moisture content levels for both cultivars are presented in Table 1.

All tests were carried out at the Biological Material Laboratory in the Department of Agricultural Machinery of Atatürk University, Erzurum, Turkey.

**Statistical analysis**

The experimental design of two bulk densities by four moisture contents by three replications within each test were conducted for each of two safflower cultivars. Analysis of variance was done to determine the significance of the effects of the variables and differences between cultivars using SPSS statistical software (IBM SPSS® Statistics, 2010).

**Results and discussion**

The effect of moisture content and bulk density on the thermal conductivity values of the safflower seeds is presented in Figure 3a for cv. Remzibey-05 and in Figure 3b for cv. Dinçer. As the moisture content increased from 5.79 to 20.38% d.b., the values of thermal conductivity of cv. Remzibey-05 increased from 0.105
to 0.132 $\text{W m}^{-1} \text{K}^{-1}$ and from 0.108 to 0.137 $\text{W m}^{-1} \text{K}^{-1}$ for low and high bulk densities, respectively. The thermal conductivity values of cv. Dinçer increased from 0.106 to 0.137 $\text{W m}^{-1} \text{K}^{-1}$ and from 0.110 to 0.140 $\text{W m}^{-1} \text{K}^{-1}$ for low and high bulk densities, respectively, while the moisture content increased from 5.07 to 20.30% d.b. As the moisture content increased the thermal conductivity values of the two safflower cultivars increased for both low and high bulk densities. A number of researchers reported that the thermal conductivities of the various seeds and grains increased as the moisture content increased, supporting our results (Kazarian and Hall, 1965; Morita and Singh, 1979; Chang, 1986; Dutta et al., 1988; Alagusundaram et al., 1991; Doğantant and Ünsal, 1991; Hsu et al., 1991; Munde, 1998; Tavman and Tawman, 1998; Singh and Goswami, 2000; Aviara and Haque, 2001; Yang et al., 2002; Subramanian and Viswanathan, 2003; Aviara et al., 2008; Hackikuru and Kocabiyik, 2008; Kocabiyik et al., 2009).

On the other hand, according to the variance analysis (Table 2), the thermal conductivity of cv. Remzibey-05 was considerably higher than that of cv. Dinçer. The difference between the thermal conductivity values of the two cultivars was significant ($p < 0.01$). Also, both bulk density and moisture content had significant effect on the thermal conductivity of the safflower seeds for both cultivars ($p < 0.01$).

From Figure 3, it can be seen that the thermal conductivity of the safflower seeds for both cultivars had higher values with high bulk density compared to low bulk density. Chang (1986) reported that thermal conductivity increased linearly with the bulk density for wheat, corn and grain sorghum, supporting our results.

Table 2. The analysis of variance of moisture contents, cultivars and bulk density for thermal conductivity

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>MS(^1)</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture content</td>
<td>3</td>
<td>0.002</td>
<td>257.308</td>
<td>0.000</td>
</tr>
<tr>
<td>Cultivar</td>
<td>1</td>
<td>0.000</td>
<td>18.124</td>
<td>0.000</td>
</tr>
<tr>
<td>Bulk density</td>
<td>1</td>
<td>0.000</td>
<td>26.054</td>
<td>0.000</td>
</tr>
<tr>
<td>Error</td>
<td>32</td>
<td>7.73 $\times 10^{-6}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>48</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^1\) MS: mean squares.

Conclusions

The thermal conductivity of safflower seeds is significantly affected by moisture content, bulk density and cultivar. Thermal conductivity of the safflower seeds increases with increase in moisture content. The thermal conductivity values of cv. Remzibey-05 seeds are higher than those of cv. Dinçer. The thermal conductivity values obtained with the high bulk density are higher than those obtained with the low bulk density for both cultivars.

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References


