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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.

Resumen

Conductividad térmica de las semillas de cártamo (*Carthamus tinctorius* L.)

Se determinó la conductividad térmica de semillas de cártamo (o alazor o azafrán bastardo) y se investigaron los cambios que se producen al variar el contenido de humedad, densidad aparente y el cultivar. Los valores de conductividad térmica del cv. Remzibey-05 aumentaron desde 0,105 hasta 0,132 W m^{-1} K^{-1} y de 0,108 a 0,137 W m^{-1} K^{-1} para las densidades aparentes bajas y altas (suelto y denso), respectivamente, en el rango de humedad de 5,79 a 20,38% en base seca. De igual forma, los valores de conductividad térmica del cv. Dinçer aumentaron de 0,106 a 0,137 W m^{-1} K^{-1} y de 0,110 a 0,140 W m^{-1} K^{-1} para densidades bajas y altas, respectivamente, en el rango de humedad de 5,07 a 20,30% en base seca. Los valores de conductividad térmica obtenidos con la alta densidad aparente fueron mayores que los obtenidos con la baja densidad aparente para ambos cultivares.

Palabras clave adicionales: contenido de humedad; densidad aparente.

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 (*Butyrospernum paradoxum*) kernel (Aviara and Haque, 2001), borage (*Borago officinalis*) seed (Yang *et al*., 2002), minor millet (*Sestaria italia, Panicum miliare, Panicum miliaceum, Paspalum sorobiculatum, Eleusine coraca-*

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Abbreviations used: DAS (data acquisition system); DC (direct current).

na, Echinochola colona) grains (Subramanian and Viswanathan, 2003), cereal grains (Kayişoğlu *et al*., 2004), guna (*Citrullus colocynthis*) seed (Aviara *et al*., 2008), black cumin (*Nigella sativa* L.) seed (Al-Mahasneh *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:

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

where T is temperature at radius r in K, t time of heating sample in s, α 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):

$$k = \frac{Q}{4\pi(T_2 - T_1)} \ln(t_2/t_1) \qquad [2]$$

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

The heat input is expressed as follows:

$$Q = VI / L \qquad [3]$$

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:

$$M_w = \frac{W(M_f - M_i)}{(100 - M_f)} \qquad [4]$$

where M_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

Safflower cultivar	Moisture content (% db)	Bulk density (kg m^{-3})
Remzibey-05	5.79	536.4
		577.1
	9.66	526.8
		577.6
	14.24	528.5
		577.0
	20.38	531.0
		578.5
Dinçer	5.07	577.5
		615.1
	9.67	566.1
		613.8
	15.45	571.7
		617.3
	20.30	572.7
		620.6

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 Al_2O_3 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* ln

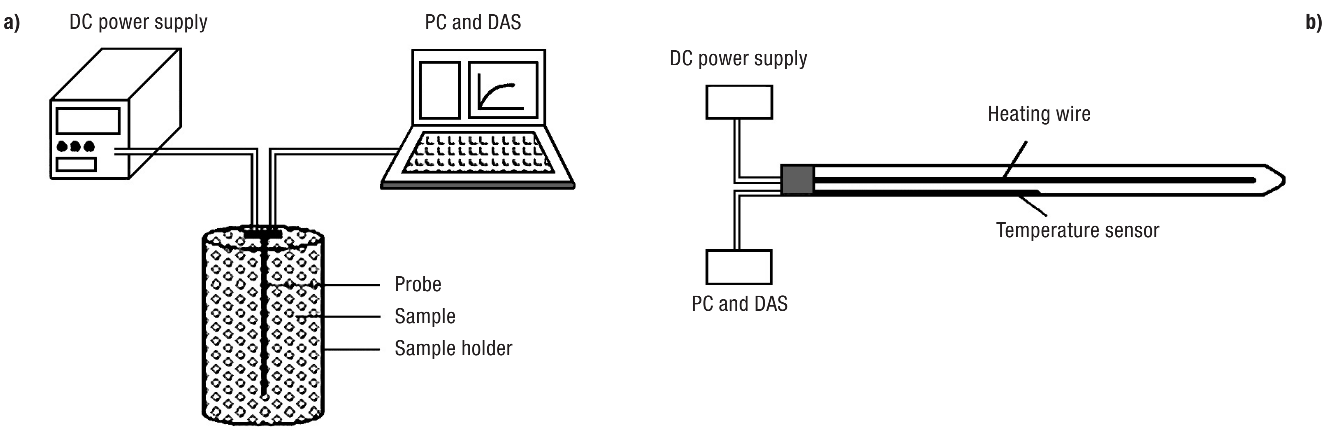

Figure 1. Thermal conductivity measurement system developed (a) and detail of the thermal conductivity probe (b). DAS: data acquisition system. DC: direct current.

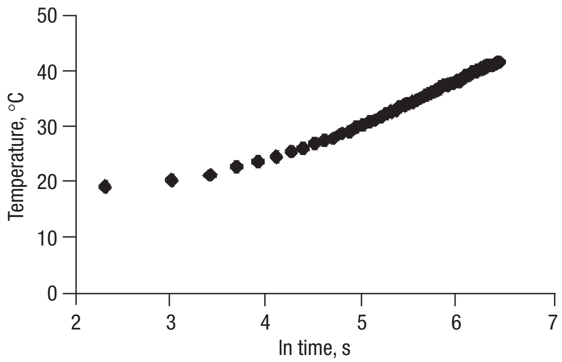

Figure 2. A typical thermogram showing the linearity of temperature *versus* ln time.

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:

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

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

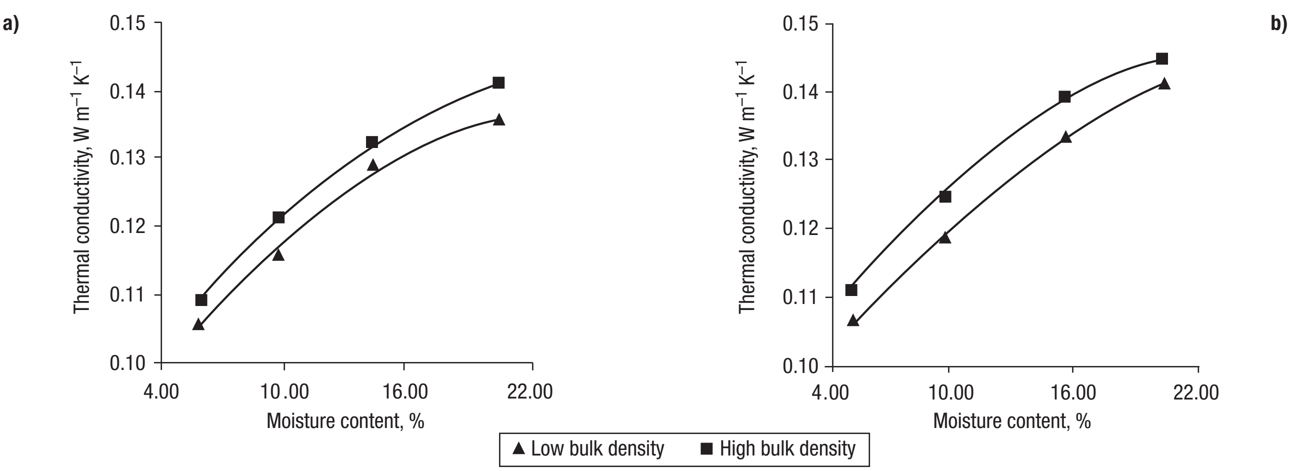

Figure 3. Thermal conductivity of safflower seeds at different moisture contents and two bulk densities for cv. Remzibey-05 (a) and Dinçer (b).

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

Source	df	MS[1]	F	*p*
Moisture content	3	0.002	257.308	0.000
Cultivar	1	0.000	18.124	0.000
Bulk density	1	0.000	26.054	0.000
Error	32	7.73×10^{-6}		
Total	48			

[1] MS: mean squares.

to 0.132 W m^{-1} K^{-1} and from 0.108 to 0.137 W m^{-1} K^{-1} for low and high bulk densities, respectively. 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, 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; Doğantan 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; Hacikuru 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.

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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