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Thermal Properties of Some Oily Seeds

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Abstract: Thermal properties namely, specific heat, thermal conductivity and thermal diffusivity of corn, soybean and sunflower were determined as a function of moisture content (w.b.) and temperature. The specific heat was measured by using mixture method and ranged from 1.4868 to 2.4224 kJ/kg°, 1.3934 to 3.1976 kJ/kg°C and 0.8649 to 1.9302 kJ/kg°C for corn, soybean and sunflower, respectively. The thermal conductivity was measured by transient technique using line heat source and varied between 0.1194 and 0.2474 W/m°C for corn, 0.0980 and 0.2276 W/m°C for soybean, 0.0929 and 0.2099 W/m°C for sunflower. The average values of thermal diffusivity ranged between 1.111×10^{-7} and 1.371×10^{-7} m^2/s for corn, 8.268×10^{-8} and 1.496×10^{-7} m^2/sfor soybean, 2.325×10^{-7} and 3.695×10^{-7} m^2/s for sunflower. Simple empirical models were developed to express thermal properties as a function of moisture content and temperature.
Key words: Specific heat, thermal conductivity, thermal diffusivity, oily seeds.

INTRODUCTION and LITERATURE REVIEW

Oily seeds give 86% of oil production of the world. Corn, soybean and sunflower are important sources of oil all over the world as well as Turkey.

Since, especially oily seeds are more heat-sensitive among the agricultural materials, the losses and decreasing in quality occur during storage and processing period due to material moisture content and external and internal temperature changes.

Therefore, the objectives of this study were to investigate the effects of the moisture content and temperature on the thermal properties namely specific heat, thermal conductivity and thermal diffusivity of corn, soybean and sunflower varieties which are extensively grown in Turkey and to develop mathematical models for prediction of these properties as a function of moisture content and temperature.

Thermal properties of agricultural material have to be known in order to develop the thermal processes and equipment needed for storage, drying, heating and cooling. Specific heat, thermal conductivity and thermal diffusivity are the most important engineering properties of biological materials related with heat transfer characteristics. Thermal properties of various agricultural materials have been studied by many researches such as Kazarian and Hall (1965) for pistachios, Murata *et al.* (1987) for cereal grains, Singh and Goswami (2000) for cumin seed, Aviara and Haque (2001) for sheanut kernel, Yang *et al.* (2002) for borage seeds, Kayışoğlu *et al.*, (2004) for cereal grains, Sabapathy and Tabil (2004) for chickpea and Kocabıyık and Tezer (2007) for rapeseed.

In agricultural materials, moisture content and temperature greatly influence the specific heat, thermal conductivity and thermal diffusivity (Singh and Goswami, 2000).

Specific heat is the mass heat capacity defined is the heat capacity of a body per unit mass of the body. It is expressed as a function of moisture content using linear relations (Mohsenin, 1980). It is also reported that the specific heat increased linearly with temperature for wheat, peanuts and gram. (Muir and Viravanichai, 1972; Suter *et al.*, 1975; Dutta *et al.*, 1988). Generally, the method of mixtures was used by many researchers for the determination of specific heat (Shrivastava and Datta, 1999; Subramanian and Viswanathan, 2003; Razavi and Taghizadeh, 2007).

Thermal conductivity is the quantity of heat that flow in unit time across unit area between two surfaces. Variations of thermal conductivity with respect to moisture content and temperature have been reported as linear by many researchers (Sweat and Haugh, 1974; Desphande *et al.*, 1996; Aviara and Haque, 2001; Yang *et al.*, 2002; Kocabıyık and Tezer, 2007). Thermal conductivity measuring methods can be classified into two categories: steady-state and transient-state heat transfer methods. Among these methods, second method is more suitable for agricultural methods (Mohsenin, 1980). Furthermore, the line heat source method is the most common transient-state method which is used by many researchers (Dutta *et al.*, 1988; Sabapathy and Tabil, 2004; Kayışoğlu *et al.*, 2004)

Thermal diffusivity may be considered as the rate at which heat is diffused out of the materials. Most of the methods for determination of thermal diffusivity reported in the literature are indirect in that it is calculated by using thermal conductivity, specific heat and bulk density (Mohsenin, 1980). Most of the previous studies have been showed that the effect of moisture content and temperature generally, can be expressed as polynomial (Singh and Goswami, 2000; Aviara and Haque, 2001).

MATERIAL and METHOD

As test materials, Pioneer, A3127 and Sanbro varieties were used for corn, soybean and sunflower, respectively. The test materials were obtained from local farms in Çukurova Region. The seeds were cleaned manually to remove dust and foreign materials. The moisture contents of seeds were determined by oven drying at 105 C for 24 h. In order to obtain higher moisture contents, predetermined quantity of distilled water was added and the samples were packed. Then they were kept at 4 °C in the refrigerator for 3 days to distribute the moisture uniformly. For obtaining different temperature levels, the samples were heated in microwave oven for known durations. The bulk density of materials at desired levels was achieved by filling up to certain height.

All experiments in this study were repeated three times at different moisture content and temperature levels. The individual and combined effects of independent variables (moisture content and temperature) on specific heat, thermal conductivity and thermal diffusivity were analyzed based on the two factor completely randomized design by using MSTATC statistical software program. The model equations were developed by using Sigmaplot software program. The test materials' bulk densities at moisture content investigated in the study and independent variables' values were given in Table1.

Table 1. The bulk densities of the test material and independent variables' values investigated in the study.

Material	Bulk density (kg/m^3)	Moisture content, w.b. (%)			Temperature (°C)		
		Specific heat	Thermal conductivity	Thermal diffusivity	Specific heat	Thermal conductivity	Thermal diffusivity
Corn						10	
	808	6.8	6.3	6.5	35	20	35
	793	11.6	12.1	11.9	50	35	50
	782	20.3	18.5	19.4	65	50	65
	775	27.5	24.5	26.0	80	65	80
						80	
Soybean						10	
	730	6.2	5.6	6.2	35	20	35
	725	13.4	10.4	13.4	50	35	50
	716	21.2	19.7	21.2	65	50	65
	670	30.4	31.5	30.4	80	65	80
						80	
Sunflower						10	
	464	5.8	6.2	5.8	35	20	35
	440	12.8	13.8	12.8	50	35	50
	428	22.6	20.3	22.6	65	50	65
	420	30.7	29.7	30.7	80	65	80
						80	

* All values are average.
* Bulk density values are in order from low to high moisture contents.

The method of mixtures is the most suitable technique mentioned in the literature for measuring specific heat of agricultural materials (Mohsenin, 1980; Razavi and Taghizadeh, 2007). This method is based on assumption that the heat loss of hot source is equal to heat gained by the cold source in the isolated ambiance. In this method, the samples at a known mass and temperature is dropped into a calorimeter of known specific heat containing water at a known temperature and weight. The calorimeter used in the tests was composed of thermoflask and insulating material. Also, a cylindrical glass 100 mm in height, 15 mm in diameter and 1.5 mm wall thickness was used as test capsule.

For determining of heat capacity of calorimeter, a known quantity of distilled water at a known lower temperature was added to calorimeter contained distilled water at higher temperature. The calorimeter was sealed and shaken every 5 minutes. It is assumed
that the system is adiabatic. Hence, the heat capacity of calorimeter was calculated by using Equation 1 (Shrivastava and Datta, 1999; Razavi and Taghizadeh, 2007):

$$H_f = \frac{M_{cw}C_w(T_e - T_{cw}) - M_{hw}C_w(T_{hw} - T_e)}{(T_{hw} - T_e)} \qquad (1)$$

where; H_f is the heat capacity of calorimeter in kJ/°C, M_{cw} is the mass of the cold water in kg, C_w is the specific heat of the water in kJ/kg°C, T_e is the equilibrium temperature in °C, T_{cw} is the temperature of the cold water in °C, M_{hw} is the mass of the hot water in kg, and T_{hw} is the temperature of the hot water in °C.

For determining heat capacity of test capsule, the empty capsule at high temperature was dropped into calorimeter contained called water and the temperature changes were obtained. Equation 2 was used to compute the heat capacity of tests capsule, H_c in kJ/°C (Shrivastava and Datta, 1999; Razavi and Taghizadeh, 2007):

$$H_c = \frac{(H_f + M_{cw}C_w)(T_e - T_{cw})}{(T_c - T_e)} \qquad (2)$$

where; T_c is the temperature of the capsule in °C.

Then, the test capsule containing samples at high temperature was dropped into calorimeter contained distilled water at low temperature. The temperature changes of both samples and water were recorded by using TES 1307 K/J thermometer and two k type thermocouples. After the system reached the heat balance, the specific heat of samples was calculated by Equation 3 (Mohsenin, 1980; Shrivastava and Datta, 1999). The measurement system is showed in Figure 1.

$$C_p = \frac{(H_f + M_{cw}C_w)(T_e - T_{cw}) - H_c(T_s - T_e)}{M_s(T_m - T_e)} \qquad (3)$$

where; C_p is the specific heat of the material in kJ/kg°C, T_s is the temperature of the sample in °C and M_s is the mass of the sample in kg.

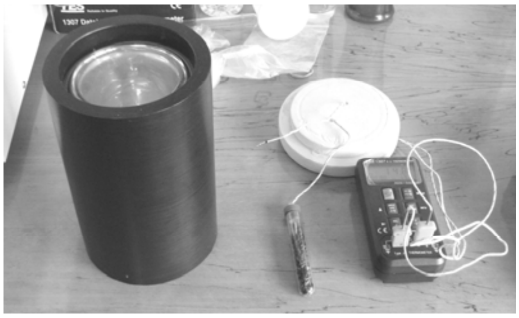

Figure 1. Specific heat measurement system

The line source method was used to measure the thermal conductivity of samples (Kayışoğlu *et al.*, 2004; Sabapathy and Tabil, 2004). This uses the transient-state method. This method uses either a bare wire or a thermal conductivity probe as a heating source and estimates the thermal conductivity based on the relationship between the sample temperature and heating time. In this study, KD2 Thermal Properties Analyzer (Decagon Devices, Inc.) was used (Figure 2). Some of its specifications were given in Table 2.

Figure 2. KD2 Thermal Properties Analyzer

Table 2. Specifications of KD2 Thermal Properties Analyzer

Specifications	Range
Measurement speed	1.5 min
Accuracy	5% thermal conductivity/resistivity
Operating environment	-20 to 60 °C
Range of measurement	0.02-2 W/m°C (Conductivity) 0.5-50 m°C/W (Resistivity)
Needle length	60 mm
Needle diameter	1.28 mm
Cable length	72 cm

The thermal diffusivity of samples was calculated using the experimental values of specific heat, thermal conductivity and bulk density from the Eq. 4 (Singh and Goswami, 2000; Irtwange and Igbeka, 2003):

$$\alpha = \frac{k}{\rho C_p} \tag{4}$$

where; α is the thermal diffusivity in m2/s, k is the thermal conductivity in W/m°C and ρ is the bulk density in kg/m^3.

RESEARCH RESULTS

The variation in specific heat with moisture content and temperature of corn, soybean and sunflower is presented in Figure 3.

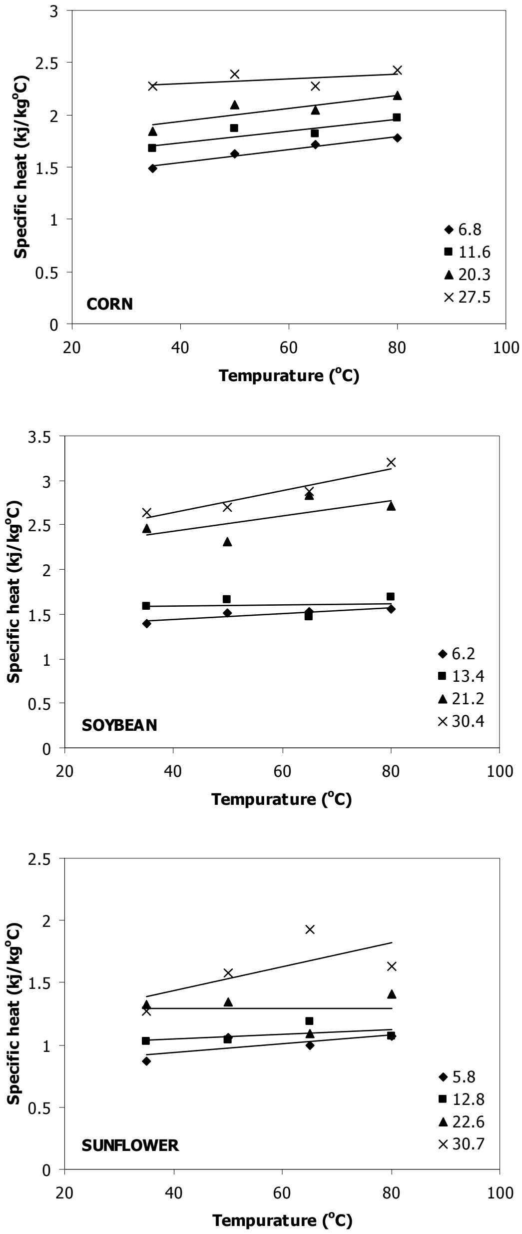

Figure 3. The variation of specific heat with moisture content (w.b) and temperature.

As seen in Figure 3, there was a linear relationship between specific heat and independent variables for all seeds. Moreover, the specific heat increased with an increase in moisture content and temperature. It was found that, within the experimental limits tested in this study, the moisture content affected specific heat at 1% level of significance, while temperature has no significant effect for all seeds. The average specific heat values varied from 1.4868 to 2.4224 kJ/kg°C for corn, from 1.3934 to 3.1976 kJ/kg°C for soybean and from 0.8649 to 1.9302 kJ/kg°C for sunflower. Based on the experimental data, the specific heat of seeds tested here was expressed through linear regression equations as a function of moisture content (M) and temperature (T) as follows.

Corn C_p=1.1444+0.0320M+0.0051T (R^2=0.98)
Soybean C_p=0.6607+0.0627M+0.0062T (R^2=0.97)
Sunflower C_p=0.5934+0.0241M+0.0038T (R^2=0.96)

The average thermal conductivity values were found to lie between 0.1194 and 0.2474 W/m°C for corn, 0.0980 and 0.2276 W/m°C for soybean, 0.0929 and 0.2099 W/m°C for sunflower with in experimental moisture content and temperature ranges tested in this study. The variation of thermal conductivity with moisture content and temperature is shown Figure 4.

From Figure 4, it can be seen that the thermal conductivity increased with increase in moisture content and temperature for all seeds. It was also found that the effect of moisture content and temperature was highly significant (1% level of significance) on the thermal conductivity of all seeds. The thermal conductivity was modeled in the form of linear regression equations:

Corn k=0.0797+0.0048M+0.0006T (R^2=0.99)
Soybean k=0.0773+0.0031M+0.0006T (R^2=0.99)
Sunflower k=0.0694+0.0036M+0.0004T (R^2=0.99)

Figure 5 presents the variation of the thermal diffusivity values as a function of moisture content and temperature. It can be observed that the thermal diffusivity of all seeds increase with increase in moisture content generally and the relationship between them is linear. Unlikely, a clear relationship between thermal diffusivity of all seeds and the temperature tested in this study cannot be found. The average values of thermal diffusivity ranged between 1.111×10^{-7} and 1.371×10^{-7} m^2/s for corn, 8.268×10^{-8} and 1.496×10^{-7} m^2/sfor soybean, 2.325×10^{-7} and 3.695×10^{-7} m^2/s for sunflower.

The results of analysis showed that while, thermal diffusivity was influenced by moisture content (1% level of significance), temperature, within the experimental limits tested in this study has not a significant effect on thermal diffusivity. However, the combined effect of moisture content and temperature on thermal diffusivity was represented by linear equations:

Corn $\alpha=9.893\times10^{-008}+1.15\times10^{-009}M+7.196\times10^{-011}T$ (R^2=0.98)
Soybean $\alpha=1.893\times10^{-007}-5.100\times10^{-010}M+1.511\times10^{-010}T$ (R^2=0.96)
Sunflower $\alpha=2.615\times10^{-007}+2.265\times10^{-009}M-9.169\times10^{-011}T$ (R^2=0.96)

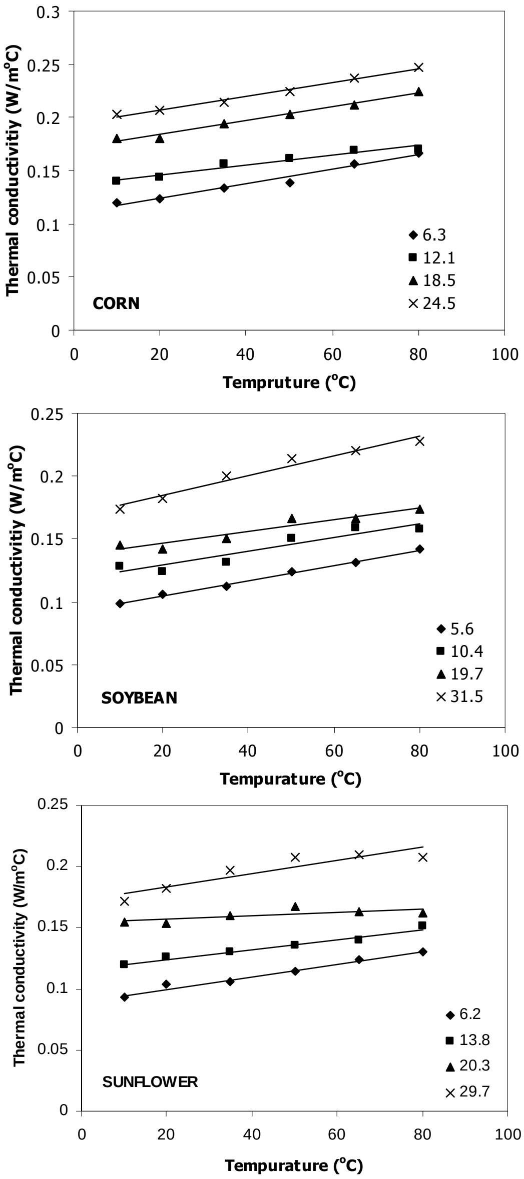

Figure 4. The variation of thermal conductivity with moisture content (w.b.) and temperature.

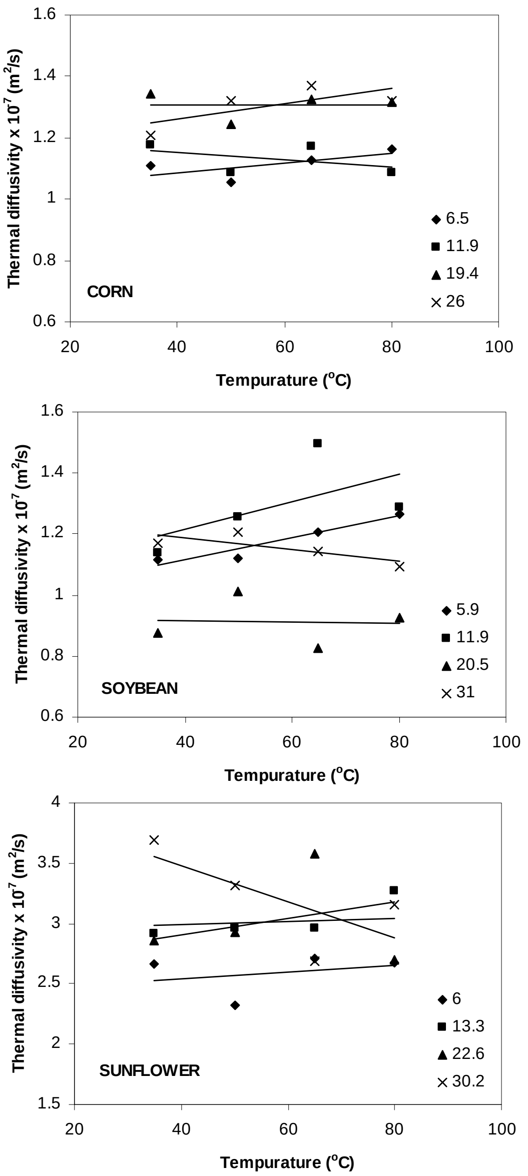

Figure 5. The variation of thermal diffusivity with moisture content (w.b) and temperature.

DISCUSSION and CONCLUSIONS

The analysis of test results showed that the moisture content was more significant than temperature on dependent variables (specific heat, thermal conductivity and thermal diffusivity). This trend has been also reported by Shrivastava and Datta (1999) for mushrooms and Singh and Goswami (2000) for cumin seed. The relationships between independent and dependent variables within the ranges investigated in this study were expressed linearly for all seeds as reported previously by many researchers (Hsu *et al.*, 1991; Chandrasekar and Viswanathan, 1999; Aviara and Haque, 2001; Kocabıyık and Tezer, 2007). Owing to high correlation coefficients (R^2) obtained for model equations, they can be used for prediction of the thermal properties within the experimental limits tested in this study.

In Fig 3, it can be seen that especially at high moisture contents the specific heat increased rapidly when the temperature increased for all seeds. Same trend is also clear for thermal conductivity. The reason for this is that heat transfer occurs easily at high moisture content due to water content of the material.

Considering average specific heat values, soybean has the highest value and corn and sunflower follows it respectively. While corn has the highest average thermal conductivity value (0.1793 W/m°C), the average values for soybean (0.1551 W/m°C) and sunflower (0.1503 W/m°C) were almost equal. The thermal conductivity values found in this study were also in agreement with findings reported by Kayışoğlu *et al.* (2004).

For this study, it can be generally said that thermal diffusivity increased with increasing moisture content for all seed. But, a clear relationship could not be found between thermal diffusivity and temperature in the range of this study. This can be because the magnitude of thermal diffusivity depends on the combined effect of specific heat, thermal conductivity and bulk density. Uncertainty effect of temperature on specific heat and thermal conductivity resulted uncertainties in thermal diffusivity. The overall average thermal diffusivity values were found to be 1.214×10^{-7}, 1.134×10^{-7} and $2.962\times10^{-7}$for corn, soybean and sunflower, respectively.

Results of this study showed the significant variation in specific heat, thermal conductivity and thermal diffusivity of corn, soybean and sunflower with changing moisture content within the experiment limits of this study while the changing the temperature was not significant on them. High correlation coefficients allowed the expression of relationships between dependent and independent variables as linear.

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