Determination of Thermal Conductivity, Specific Heat and Thermal Diffusivity of Borage Seeds

W. Yang1; S. Sokhansanj 2; J. Tang 3; P. Winter 4

1 Department of Food Science, University of Arkansas, 2650 N. Young Ave., Fayetteville, AR 72704, USA; e-mail of corresponding author: wyang@uark.edu
2 Oak Ridge National Lab, Bioenergy Feedstock Development Program, Oak Ridge, TN 37831-6422, USA; e-mail: sokhansanjs@ornl.gov
3 Food Engineering Program, Department of Biological Systems Engineering, Washington State University, Pullman, WA 99164-6120, USA; e-mail: jtang@mail.wsu.edu
4 Hinz Automation, Inc., 410 Jessop Ave., Saskatoon, SK, Canada S7N 2S5; e-mail: phil.winter@sask.hinz.com

(Received 16 March 1999; accepted in revised form 15 February 2002; published online 11 June 2002)

Thermal conductivity, specific heat capacity and thermal diffusivity of borage (Borago officinalis) seeds were determined at temperatures ranging from 6 to 20°C and moisture contents from 1.2 to 30.3% w.b. The thermal conductivity was measured by the transient technique using a line heat source. The maximum slope method was used to analyse the line source heating data for thermal conductivity determination. The specific heat capacity was measured by different scanning calorimetry and ranged from 0.177 to 0.199 kJ kg⁻¹ K⁻¹. The thermal conductivity of borage seeds ranged from 0.111 to 0.28 W m⁻¹ K⁻¹ and increased with moisture content in the range of 1.2–30.3% w.b. The thermal diffusivity ranged from 2.32 × 10⁻⁷ to 3.18 × 10⁻⁷ m² s⁻¹. Bulk density of borage seeds followed a parabolic relationship with moisture content. Uncertainty analysis revealed that variation in the thermal conductivity contributed mostly to the accuracy of the thermal diffusivity.

1. Introduction

Borage is a speciality oilseed with a high content of crude oil (33%) and crude protein (28%). It is especially high in gamma linolenic acid which is currently in great demand for pharmaceutical and health-care applications. Thermal conductivity, thermal diffusivity and specific heat capacity are three important engineering properties of a material related to heat transfer characteristics. These parameters are essential in studying heating, drying and cooling processes for borage seeds. Thermal properties of many agricultural and food products have been reported in the literature, and most of these data are compiled by Polley et al. (1980) and ASAE (2001) for engineering research and design purposes. The thermal property data of many novelty crops are not, however, available in the literature. For borage seeds, no other thermal property data than the specific heat capacity as reported by Yang et al. (1997) can be found in the literature.

Thermal conductivity, thermal diffusivity and specific heat capacity each can be measured by several well-established methods (Mohsenin, 1980; Dickerson, 1965), but measuring any two of them would lead to the third through the relationship

\[ \alpha = \frac{k}{\rho c_p} \]  

where \( \alpha \) is the thermal diffusivity, \( k \) is the thermal conductivity, \( \rho \) is the bulk density and \( c_p \) is the specific heat.

Methods for measuring thermal conductivity can be classified into two broad categories: steady- and transient-state heat transfer methods (Mohsenin, 1980). The tests using steady-state methods often require a long time to complete and moisture migration may introduce significant measurement errors (Mohsenin, 1980; Kazarian & Hall, 1965; Dutta et al., 1988). The latter methods are more suitable for biological materials that are generally heterogeneous and often contain high moisture content. The line source method is the most widely used 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 core temperature and the heating time. In principle, the heat is generated in a hot wire at a rate \( q \) in W:

\[
q = I^2 R
\]

(2)

where \( I \) is the electric current in A and \( R \) is the electric resistance in \( \Omega \) m\(^{-1}\). For a long cylindrical sample, where the end effects and the mass of the hot wire can be neglected and when the sample is homogeneous and isotropic, heat conduction in the sample is governed by the following equation (in cylindrical coordinates), assuming that \( k \) remains constant:

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

(3)

where \( T \) is the sample temperature anywhere in the cylinder in °C, \( t \) is the time in s, \( r \) is the radial axis in m, and \( \alpha \) is the thermal diffusivity in m\(^2\)s\(^{-1}\). The solution to Eqn (3) is (Hooper & Lepper, 1950)

\[
T - T_0 = \frac{q}{2\pi k} F(n)
\]

(4)

where \( T_0 \) is the initial sample temperature, \( n \) is an intermediate variable and

\[
F(n) = A - \ln(n) + \frac{(rn)^2}{2} - \frac{(rn)^4}{8} + \cdots
\]

(5)

\[
n = \frac{1}{2} (2n)^{-1/2}
\]

(6)

where \( A \) is a constant. If the product of \( r \) and \( n \) is very small, namely, a negligibly small value for \( r \) and a large value for \( t \), Eqn (5) can be approximated by the first two terms:

\[
T - T_0 = \frac{q}{2\pi k} \left\{ A - \ln(n) \right\}
\]

(7)

or

\[
T - T_0 = \frac{qA}{2\pi k} - \frac{q}{2\pi k} \ln \left( \frac{1}{2\pi k} - \frac{1}{2} \right) + \frac{q}{4\pi k} \ln(t)
\]

(8)

Equation (8) shows a linear relationship between \( T - T_0 \) and \( \ln(t) \) with the slope \( S = q/(4\pi k) \). The slope \( S \) can be obtained from the experimental data of \( T - T_0 \) versus \( \ln(t) \) by linear regression, and the thermal conductivity can then be calculated from the linear slope \( S \):

\[
k = \frac{I^2 R}{4\pi S}
\]

(9)

Owing to non-ideal conditions in reality, such as non-zero mass and volume of the hot wire, heterogeneous and anisotropic properties of biological materials, finite sample size and axial heat flow (Mohsenin, 1980; Suter et al., 1975; Wang & Hayakawa, 1993), temperature rise \( T - T_0 \) versus \( \ln(t) \) does not always follow a linear relationship. This calls for correction during data reduction. The most used early method for data correction was the time-correction factor method (Van der Held & Van Drunen, 1949), which minimized the non-linearity of the \( T - T_0 \) versus \( \ln(t) \) curve by subtracting a factor from the time elapsed. Murakami and Okos (1988) proposed a method using the maximum coefficient of determination \( (R^2) \) for the correction, which searched for a maximum linear portion of the curve by successive linear regression using \( R^2 \) values as a criteria for the maximum linearity. Wang and Hayakawa (1993) verified, theoretically and experimentally, the maximum slope method that was first used by Asher et al. (1986). This method calculates the thermal conductivity using the maximum slope around a plateau of the local slope versus \( \ln(t) \) plot. The study of Wang and Hayakawa (1993) showed that the thermal conductivities determined using the maximum slope method are comparable or more accurate than the time-correction method and the maximum \( R^2 \) method.

Among the published methods for specific heat measurement, differential scanning calorimetry (DSC) has so far been the most accurate and rapid method. Tang et al. (1991) reviewed the literature on the measurement of specific heat for agricultural products, and provided analyses on the key factors that can affect the specific heat measurement using the DSC method. Yang et al. (1997) described DSC procedures for measuring the specific heat of borage seeds, and developed a model to correlate the specific heat with temperature and moisture content. They also studied the
The factors that influenced the values for the specific heat of borage seeds.

The objective of this study is to determine the thermal conductivity, specific heat capacity and thermal diffusivity of borage seeds as a function of seed moisture content and temperature.

2. Materials and methods

2.1. Sample preparation

Borage (*Borago officinalis*) seeds at 6.7% initial moisture content on a wet basis (w.b.) were obtained from a seed cleaning facility. The seeds were conditioned to nine different moisture contents ranging from 1.2 to 30.3% w.b. The samples at the moisture contents below 6.7% w.b. were prepared by drying 1 kg borage seeds in a convection air oven at 75°C. The samples at the moisture contents above 6.7% w.b. were obtained by spraying pre-determined amounts of distilled water on borage seeds followed by periodic tumbling of the samples in sealed containers. The samples were then stored at 4°C before testing.

2.2. Thermal conductivity measurement

Thermal conductivity measurements were conducted in triplicate at initial temperatures of 6 and 10°C for 4.4, 9.3, 14.1, 20.2 and 29.9% w.b. moisture contents and at an initial temperature of 20°C for 1.2, 6.7, 9.3, 15.6 and 30.3% w.b. moisture contents. The bare-wire transient method (Sweat, 1986) was used. *Figure 1* shows a schematic of the equipment. It consisted of a bare-wire thermal conductivity apparatus, a 80 mm (inner diameter) cylindrical air duct, an air conditioning system, a circulating system, a data acquisition system comprising of a Campbell 21X Micrologger (Campbell Scientific Inc., Logan, UT) and a personal computer.

The bare-wire thermal conductivity apparatus consisted of a brass cylindrical sample tube 58.6 mm in inner diameter and 240 mm in length, with a removable top cover and a fixed bottom base. A 0.254 mm (diameter) constantan heater wire (10.07 Ω m⁻¹, 210 mm in length) was connected to a constant d.c. current (1.000 ± 0.004 A) power source. Pre-calibrated type T thermocouples were installed for measuring the core temperature and the outer surface temperature of the sample tube. The thermocouples were connected to the data acquisition system by a thermocouple extension wire.

In the literature, most researchers used a water bath to maintain a constant sample surface temperature while using the hot-wire method to measure thermal conductivity. A major disadvantage of using a water bath is the necessity of sealing the sample holding tube, which may be very time consuming and cumbersome, and there exists the possibility of water leakage into sample during the tests. This major disadvantage was overcome in this study by blowing high-velocity air over the outer surface of the sample tube to maintain a constant surface temperature of the sample holder. The air velocity in the annular space between the sample tube and the air duct as used in this study was around 27 m s⁻¹. *Figure 2* illustrates the temperature history of the tube surface during three measurements for the samples of 4.4, 9.3 and 14.1% w.b. moisture contents at the temperatures of 6, 10 and 20°C. The variation in temperature was mostly within 1°C except for a few points (between 1 and 2°C). The results validated the high air velocity method used in this study to maintain a constant surface temperature.

Before loading into the sample holder, the samples in sealed containers were placed in an environmental chamber for a few hours up to 12 h. This was for sample temperature to equilibrate to the chamber temperature that was set at a desired initial temperature of the sample. For each test, the sample holder was filled with borage seeds and the net weight of the sample (the sample holder weight after filling minus that before filling) was recorded for the calculation of bulk density. The temperatures of the sample core (about 1 mm from the hot wire), sample holder surface and the chamber were recorded at an interval of 5 s.
2.3. Measurement of specific heat capacity

Differential scanning calorimetry was used to determine the specific heat capacity of borage seeds at six moisture contents (1/8/1%, 2/4/1%, 4/9/1%, 6/1/2%, 8/0/1% and 10/9/1% w.b.) at temperatures ranging from 5 to 20°C. The tests were carried out in triplicate, following a similar experimental procedure described by Yang et al. (1997). In brief, a single borage seed, weighed to ±0.001 mg, was hermetically sealed in a 40 μl standard aluminium crucible, and loaded in the DSC30 cell of a TC 10 thermal analyser (Mettler Instrumente AG, Switzerland). The specific heat measurements were made between 5 and 20°C temperature at a heating rate of 5Kmin against a pre-recorded blank compensation curve (the baseline when an aluminium crucible contained no sample). Since the specific heat data of borage seeds at 6/1/7%, 8/0/1%, 10/9/1% and 20/0/1% moisture contents and 5–20°C temperatures have been reported elsewhere (Yang et al., 1997), they were quoted and used directly in this study.

2.4. Thermal diffusivity calculation

Thermal diffusivity was calculated according to Eqn (1). The average bulk density of borage seeds in kg m⁻³ was obtained by dividing the sample weight recorded each time upon completion of sample loading by the effective volume of the sample tube (tube volume minus frame volume). The bulk density was measured in situ to eliminate the influence of loading pattern and container size on bulk density measurement.

An analysis of variance was conducted at 0.01 confidence level to examine the effect of temperature and moisture content on the thermal conductivity. The Statistical Analysis System (SAS) procedures (SAS Institute Inc., Cary, NC) were used for multiple regression analysis.

The probable uncertainty for the estimated thermal diffusivity \( \alpha \) as the result of the uncertainties in the measured thermal conductivity \( k \), specific heat \( c_p \), and bulk density \( \rho \) was estimated based on the following relationship (Huggins, 1983):

\[
\alpha = \left[ \frac{\partial [z(k, c_p, \rho)]}{\partial k} \alpha_k \right]^2 + \left[ \frac{\partial [z(k, c_p, \rho)]}{\partial c_p} \alpha_{c_p} \right]^2 + \left[ \frac{\partial [z(k, c_p, \rho)]}{\partial \rho} \alpha_{\rho} \right]^2 \right]^{1/2}
\]

Substituting Eqn (1) into the above equation yields

\[
\alpha = \left[ \left( \frac{1}{pc_p} \alpha_k \right)^2 + \left( \frac{k}{pc_p^2} \alpha_{c_p} \right)^2 + \left( \frac{k}{pc_p^2} \alpha_{\rho} \right)^2 \right]^{1/2}
\]

where, \( \alpha_k \), \( \alpha_{c_p} \), and \( \alpha_{\rho} \) were estimated from repeated measurements at the 95% confidence limit.

3. Results and discussion

3.1. Thermal conductivity

Figure 3 shows the typical local slopes calculated based on the experimental data and how a maximum slope was determined. The maximum slope was used to calculate the thermal conductivity using Eqn (9). Figure 4 shows the triplicate thermal conductivity data.
of borage seeds as a function of moisture content at 6, 10 and 20°C initial temperatures. The average thermal conductivity of borage seeds varied from 0.11 to 0.28 W m⁻¹ K⁻¹, depending upon sample temperature and moisture content. The standard deviations ranged from 0.005 to 0.019 W m⁻¹ K⁻¹. The thermal conductivity of borage seeds was comparable with that of whole rapeseed (0.108–0.155 W m⁻¹ K⁻¹) at moisture contents from 6 to 12.8% w.b. and temperatures from 4.4 to 31.7°C (Mohsenin, 1980). The thermal conductivity of borage seeds was 15 and 35% higher than those of whole peanut kernels (Suter et al., 1975) and whole soyabean (Mohsenin, 1980), respectively. This difference may be attributed to the difference in kernel size, the porosity of sample bulk, and oil and protein contents. A linear relationship between average thermal conductivity and initial sample moisture content in the tested temperature and moisture ranges was observed (Fig. 4). Both temperature and moisture content had a significant effect on the thermal conductivity of borage seeds (0.01 confidence level).

Multiple regression by SAS (SAS Institute Inc., Cary, NC) was performed to fit the first- and the second-order response functions with interaction terms between temperature \( T \) and moisture content \( M \) to the thermal conductivity data. Tests of the hypothesis concerning the regression coefficients (Neter et al., 1985) were conducted at 95% confidence level to select terms in the equations. The statistical parameters, the mean per cent relative deviation (D) and standard error of the residuals (SE) (Yang & Cenkowski, 1994) were calculated to assess the fitting of the equations to the experimental data. The equation with \( T, M \) and \( TM \) terms had significant improvement in terms of D and SE values over the equation with only \( T \) and \( M \) terms. There was no significant improvement of any second-order equation over the equation with \( T, M \) and \( TM \) terms. Therefore, the resultant equation was obtained to relate thermal conductivity of borage seeds with temperature and moisture content:

\[
k = 0.097 + 1.285 \times 10^{-4} T + 1.868 \times 10^{-3} M \\
+ 1.951 \times 10^{-4} TM
\]  

(12)

The calculation yielded a D of 1.54 and SE of 0.003 for Eqn (12), suggesting that the estimated values for \( k \) were very close to the experimental data (Fig. 4). The residuals scattered randomly about the zero line as shown in Fig. 4. This indicates that Eqn (12) represented satisfactorily the thermal conductivity data of borage seeds in the temperature and moisture content ranges tested in this study.

3.2. Specific heat capacity

Table 1 lists the specific heat capacity data of borage seeds measured at temperature 6, 10 and 20°C. Most data in Table 1 were measured at moisture contents different from that reported by Yang et al. (1997). For comparison, some data for \( c_p \) that have been reported previously (Yang et al., 1997) are also listed in Table 1. The values for \( c_p \) of borage seeds ranged from 0.77 to 1.99 kJ kg⁻¹ K⁻¹ in the temperature and moisture content ranges tested in this study.
The data for $c_p$ obtained in this study were also used to verify the model developed by Yang et al. (1997), that is

$$c_p = 0.58 + 7.36 \times 10^{-3} T - 4.11 \times 10^{-5} T^2 + 3.04 \times 10^{-2} M + 1.81 \times 10^{-4} M^2 + 6.40 \times 10^{-4} TM - 1.49 \times 10^{-5} TM^2$$

(13)

which yielded a coefficient of determination of 0.99. The values for $c_p$ calculated using Eqn (13) are also listed in Table 1. The percent difference between the measured and the estimated values was mostly less than 5% (Table 1). This confirmed the applicability of the model to the values for $c_p$ of borage seeds.

### 3.3. Thermal diffusivity

Calculation of the thermal diffusivity of borage seeds $\alpha$ requires a knowledge of the bulk density of borage seeds, which was obtained by dividing the mass of borage seeds by the effective volume of the tube. The resultant bulk density data were shown in Table 2. The bulk density of borage seeds can be approximated by a second-order polynomial (parabolic) as given below:

$$\rho = 457.5 - 0.86M + 4.43 \times 10^{-2} M^2$$

(14)

which yielded a coefficient of determination of 0.999.

*Figure 5* presents the calculated thermal diffusivity values as a function of moisture content at temperatures 6, 10 and 20°C, respectively. The values for $\alpha$ ranged from 2.32 x 10^{-7} to 3.18 x 10^{-7} m^2 s^{-1} in the temperatures and moisture contents tested in this study. The thermal diffusivity values of borage seeds were between those of water (1.47 x 10^{-7} m^2 s^{-1}) and air (2.35 x 10^{-7} m^2 s^{-1}) (Jiang et al., 1986). In general, values for $\alpha$ of borage seeds decreased with increasing moisture content (*Fig. 5*). It is noted that both ascending [e.g. for gram (Dutta et al., 1988)] and descending [e.g. for haylage (Jiang et al., 1986)] trends of the relationship between $\alpha$ and $M$ have been reported. This is because the magnitude of $\alpha$ depends on the combined effects of $k$, $\rho$ and $c_p$ according to Eqn (1). In the case where the value of $k$ increases with moisture content and substantial variation in bulk density, such as haylage, thermal diffusivity generally decreases with moisture content. For the material where the value for $k$ increases faster than that for $\rho$ and $c_p$ in the same temperature and moisture ranges, such as gram, thermal diffusivity would increase with moisture content.

Uncertainty analysis was conducted based on Eqn (11) to gain an insight into the variation in the value for $\alpha$ as a result of the uncertainties in those for $k$, $\rho$ and $c_p$. This was done at one high moisture content (30-3% w.b.) and one low moisture content (1-2% w.b.) for the temperature of 20°C. For 95% confidence limit (twice the standard deviation), the information regarding the mean and standard deviation of $k$, $\rho$ and $c_p$ and the resultant $\alpha$ were obtained from statistical analysis of the experimental data and are summarized in Table 3. The calculated values of $\alpha$ were 3.18 x 10^{-7} \pm 5.19 x 10^{-8} m^2 s^{-1} for 1-2% w.b. moisture content and 2.93 x 10^{-7} \pm 4.39 x 10^{-8} m^2 s^{-1} for 30-3% w.b. moisture content (Table 3). These corresponded to a standard deviation of 2.59 x 10^{-8} and 2.19 x 10^{-8} m^2 s^{-1} and the coefficient of variation of 8.1 and 4.4 for $\alpha$ at 1.2 and 30-3% w.b. moisture content, respectively. The analysis of uncertainty in the thermal diffusivity revealed that the contribution of the variation in the value of $k$ was about an order of magnitude larger than that in $c_p$.**

### Table 1

<table>
<thead>
<tr>
<th>Moisture content, % w.b.</th>
<th>Specific heat, kJ kg^{-1} K^{-1}</th>
<th>Difference, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured(^a)</td>
<td>Estimated(^b)</td>
<td>(^c)</td>
</tr>
<tr>
<td>Temperature at 6°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.4</td>
<td>0.79</td>
<td>0.78</td>
</tr>
<tr>
<td>9.3</td>
<td>0.96</td>
<td>0.95</td>
</tr>
<tr>
<td>14.1</td>
<td>1.13</td>
<td>1.13</td>
</tr>
<tr>
<td>20.2</td>
<td>1.34</td>
<td>1.35</td>
</tr>
<tr>
<td>29.9</td>
<td>1.71</td>
<td>1.73</td>
</tr>
<tr>
<td>Temperature at 10°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.4</td>
<td>0.82</td>
<td>0.81</td>
</tr>
<tr>
<td>9.3</td>
<td>1.04</td>
<td>1</td>
</tr>
<tr>
<td>14.1</td>
<td>1.2</td>
<td>1.18</td>
</tr>
<tr>
<td>20.2</td>
<td>1.42</td>
<td>1.41</td>
</tr>
<tr>
<td>29.9</td>
<td>1.79</td>
<td>1.78</td>
</tr>
<tr>
<td>Temperature at 20°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>0.77</td>
<td>0.76</td>
</tr>
<tr>
<td>6.7</td>
<td>1.07</td>
<td>1</td>
</tr>
<tr>
<td>9.3</td>
<td>1.14</td>
<td>1.10</td>
</tr>
<tr>
<td>15.6</td>
<td>1.31</td>
<td>1.36</td>
</tr>
<tr>
<td>30.3</td>
<td>1.99</td>
<td>1.91</td>
</tr>
</tbody>
</table>

\(^a\)Average of three replicates (SD less than 0.05).  
\(^b\)Estimated using Eqn (13).  
\(^c\)Equal to: 100[(measured—estimated)/measured].  
\(^d\)Data quoted from Yang et al. (1997).

### Table 2

<table>
<thead>
<tr>
<th>Moisture content, % w.b.</th>
<th>Bulk density, kg m^{-3}</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature at 6°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.4</td>
<td>456.6</td>
<td>0.9</td>
</tr>
<tr>
<td>9.3</td>
<td>454.7</td>
<td>2.1</td>
</tr>
<tr>
<td>14.1</td>
<td>453.8</td>
<td>1.1</td>
</tr>
<tr>
<td>20.2</td>
<td>453.1</td>
<td>0.8</td>
</tr>
<tr>
<td>29.9</td>
<td>454.5</td>
<td>1.7</td>
</tr>
<tr>
<td>Temperature at 10°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.4</td>
<td>454.9</td>
<td>1.5</td>
</tr>
<tr>
<td>9.3</td>
<td>458.2</td>
<td>1.3</td>
</tr>
<tr>
<td>14.1</td>
<td>472.1</td>
<td>2.3</td>
</tr>
<tr>
<td>Temperature at 20°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>71.07</td>
<td>86</td>
</tr>
<tr>
<td>4.4</td>
<td>71.07</td>
<td>86</td>
</tr>
<tr>
<td>9.3</td>
<td>71.07</td>
<td>86</td>
</tr>
<tr>
<td>14.1</td>
<td>71.07</td>
<td>86</td>
</tr>
<tr>
<td>20.2</td>
<td>71.07</td>
<td>86</td>
</tr>
<tr>
<td>29.9</td>
<td>71.07</td>
<td>86</td>
</tr>
</tbody>
</table>
which was, in turn, about an order of magnitude larger than the contribution of the variation in the measured value of \( r \).

Similar to the data for \( k \), the calculated values of \( a \) were fitted to multiple regression models up to the second order using SAS. There was no significant improvement in the values of D and SE for a second-order model over that with \( T \), \( M \) and \( TM \) terms (significant level 0.01). The best equation to represent the relationship of \( a \) versus \( M \) and \( T \) is

\[
a = \left(3.24 - 1.11 \times 10^{-2}T - 4.044 \times 10^{-2}M + 1.92 \times 10^{-3}TM \right) \times 10^{-7} \tag{15}
\]

The values for \( a \) estimated by Eqn (15) are also shown in Fig. 5 in comparison with the values for \( a \) calculated by Eqn (1). It seemed from Fig. 5 that Eqn (15) fit the values of \( a \) better at 6 and 10°C than at 20°C. For the three temperature levels, D and SE were 2.64 and 0.12, respectively, on an average. Thus, Eqn (15) is a fairly good model for estimating the values of \( a \).

### 4. Conclusions

(1) The thermal conductivity of borage seeds increased from 0.11 to 0.28 W m\(^{-1}\) K\(^{-1}\) at the initial temperatures between 6 and 20°C and moisture contents from 1.2 to 30.3% w.b. Both temperature and moisture content had significant effect on the thermal conductivity of borage seeds (0.01 confi-

### Table 3

Uncertainty analysis of thermal diffusivity at two extreme moisture contents at 20°C

<table>
<thead>
<tr>
<th>Moisture content, % w.b.</th>
<th>Thermal conductivity, (W m^{-1}K^{-1})</th>
<th>Density, (kg m^{-3})</th>
<th>Specific heat, (kJ kg^{-1}K^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>95% confidence limit</td>
<td>Mean</td>
</tr>
<tr>
<td>1.2</td>
<td>0.112</td>
<td>0.018</td>
<td>456.6</td>
</tr>
<tr>
<td>30.3</td>
<td>0.275</td>
<td>0.04</td>
<td>472.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Moisture content %w.b.</th>
<th>Thermal diffusivity, m(^2)s(^{-1})</th>
<th>SD</th>
<th>Coefficient of variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2</td>
<td>(3.18 \times 10^{-7})</td>
<td>(5.19 \times 10^{-8})</td>
<td>2.59 \times 10^{-8}</td>
</tr>
<tr>
<td>30.3</td>
<td>(2.93 \times 10^{-7})</td>
<td>(4.39 \times 10^{-8})</td>
<td>2.19 \times 10^{-8}</td>
</tr>
</tbody>
</table>
A first-order multiple regression model with an interaction term approximated closely the thermal conductivity data of borage seeds.

(2) The specific heat of borage seeds varied from 0.77 to 1.99 kJ kg\(^{-1}\) K\(^{-1}\) in 6–20°C initial temperature and 1.2–30.3% w.b. moisture content range. The specific heat model, previously developed, fitted well the specific heat data collected in this study, confirming the applicability of this model to the specific heat capacity of borage seeds.

(3) The thermal diffusivity of borage seeds ranged from \(2.32 \times 10^{-7}\) to \(3.18 \times 10^{-7}\) m\(^2\) s\(^{-1}\) at temperatures from 6 to 20°C and moisture contents from 1.2 to 30.3% w.b. A first-order response function can best represent the relationship of the thermal diffusivity versus temperature and moisture content. Uncertainty analysis revealed that the variations in the thermal conductivity contributed mostly to uncertainty in the thermal diffusivity.

References


Hooper F C; Lepper F R (1950). Transient heat flow apparatus for determination of thermal conductivity. Transactions of the ASHVE, 56, 309–322


Kazarian E A; Hall C W (1965). The thermal properties of grain. Transactions of the ASAE, 8(1), 33–37, 40


Suter D A; Agrawal K K; Clary B L (1975). Thermal properties of peanut pods, hulls and kernels. Transactions of the ASAE, 18, 370–375


