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

W. Yang[1]; 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

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 0·77 to 1·99 kJ kg^{-1} K^{-1}. The thermal conductivity of borage seeds ranged from 0·11 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 $2·32 \times 10^{-7}$ to $3·18 \times 10^{-7}$ m^2 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. © 2002 Silsoe Research Institute. Published by Elsevier Science Ltd. All rights reserved

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

$$\alpha = \frac{k}{\rho c_p} \qquad (1)$$

where α is the thermal diffusivity, k is the thermal conductivity, ρ 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

---

Notation

A	Constant
c_p	specific heat, $kJ\,kg^{-1}\,K^{-1}$
F	a function
I	electric current, A
k	thermal conductivity, $W\,m^{-1}\,K^{-1}$
M	moisture content, per cent wet basis
n	an intermediate variable
q	heat transfer rate, W
r	radial axis, m
R	electric resistance per unit length, $\Omega\,m^{-1}$
r^2	coefficient of determination
S	Slope
t	time, s
T	temperature, °C
T_0	initial temperature, °C
α	thermal diffusivity, $m^2\,s^{-1}$
ρ	average bulk density, $kg\,m^{-3}$
ω_α	uncertainty in thermal diffusivity
ω_κ	uncertainty in thermal conductivity
ω_c	uncertainty in specific heat
ω_ρ	uncertainty in bulk density

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:

$$q = I^2 R \tag{2}$$

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:

$$\frac{\partial T}{\partial t} = \alpha\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right) \tag{3}$$

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 α is the thermal diffusivity in $m^2\,s^{-1}$. The solution to Eqn (3) is (Hooper & Lepper, 1950)

$$T - T_0 = \frac{q}{2\pi k}F(rn) \tag{4}$$

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

$$F(rn) = A - \ln(rn) + \frac{(rn)^2}{2} - \frac{(rn)^4}{8} + \cdots \tag{5}$$

$$n = \tfrac{1}{2}(\alpha t)^{-1/2} \tag{6}$$

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:

$$T - T_0 = \frac{q}{2\pi k}[A - \ln(rn)] \tag{7}$$

or

$$T - T_0 = \frac{qA}{2\pi k} - \frac{q}{2\pi k}\ln\left(\frac{1}{2}r\alpha^{-1/2}\right) + \frac{q}{4\pi k}\ln(t) \tag{8}$$

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:

$$k = \frac{I^2 R}{4\pi S} \tag{9}$$

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

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 (*Boragoofficinalis*) 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 ($10·07 \, \Omega \, m^{-1}$, 210 mm in length) was connected to a constant d.c. current ($1·000 \pm 0·004$ 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 con-
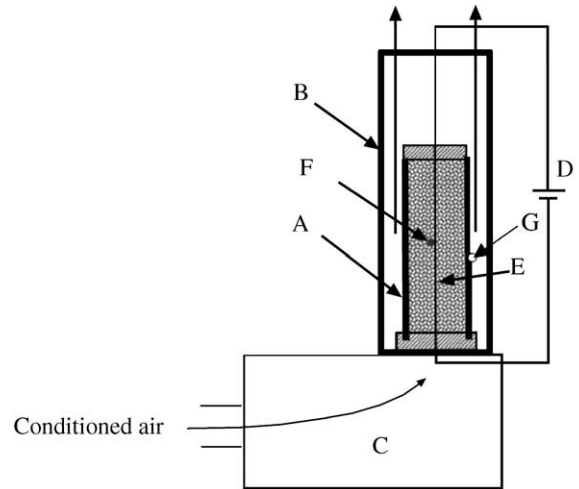

Fig. 1. Schematic of the apparatus for thermal conductivity measurement; A, bare-wire apparatus; B, air duct; C, air plenum; D, DC power supply; E, heater wire; F, thermocouple for core temperature measurement; G, thermocouple for surface temperature measurement

ductivity. 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.
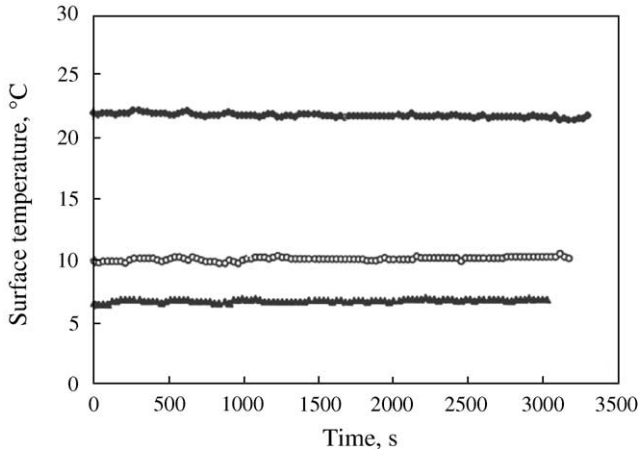
Fig. 2. Surface temperature history of the sample tube for three different measurements; ●●●●, *the sample at moisture content (MC) of 4·4% and mean surface temperature (T) of 10·3°C;* ◆◆◆◆, *the sample at MC of 9·3% and T of 21·8°C;* ▲▲▲▲, *the sample at MC of 14·1% and T of 6·8°C*

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 (1·2, 4·4, 9·3, 14·1, 20·2 and 29·9% 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 TA 3000 system (Mettler Instrumente AG, Switzerland). The specific heat measurements were made between 5 and 20°C temperature at a heating rate of 5 K min^{-1} 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 6·7, 15·6, 20·2 and 30·3% w.b. 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 ω_α as the result of the uncertainties in the measured thermal conductivity ω_k, specific heat ω_c, and bulk density ω_ρ was estimated based on the following relationship (Huggins, 1983):

$$\omega_\alpha = \left[\left(\frac{\partial\left[\alpha(k, c_p, \rho)\right]}{\partial k} \omega_k \right) + \left(\frac{\partial\left[\alpha(k, c_p, \rho)\right]}{\partial c_p} \omega_c \right) \right. $$
$$\left. + \left(\frac{\partial\left[\alpha(k, c_p, \rho)\right]}{\partial \rho} \omega_\rho \right) \right]^{1/2} \quad (10)$$

Substituting Eqn (1) into the above equation yields

$$\omega_\alpha = \left[\left(\frac{1}{\rho c_p} \omega_k \right) + \left(\frac{k}{\rho c_p^2} \omega_c \right) + \left(\frac{k}{\rho^2 c_p} \omega_\rho \right) \right]^{1/2} \quad (11)$$

where, ω_k, ω_c, and ω_ρ 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
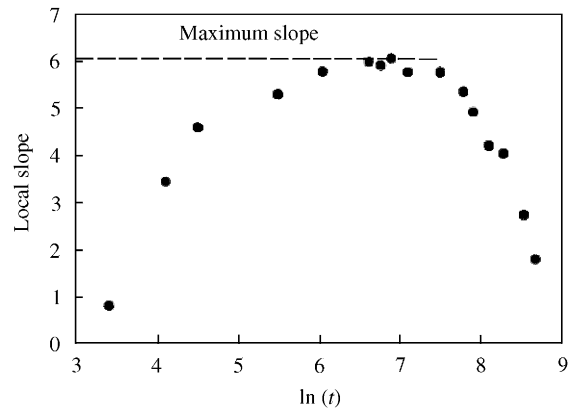

Fig. 3. An example showing how a maximum slope was determined based on the relationship of local slope values versus ln(t), where t is the time in seconds
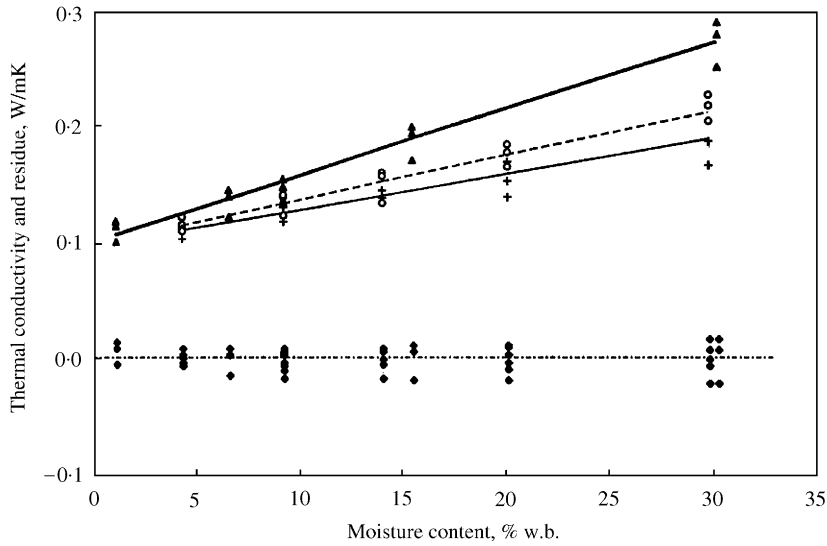
Fig. 4. The measured (scattered dots) and the estimated (lines) values of thermal conductivites and their residuals (solid diamond) in relation to moisture contents for three temperatures: ▲, 20°C; ○, 10°C; and ✚, 6°C

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 6·1 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:

$$k = 0·097 + 1·285 \times 10^{-4} \, T + 1·868 \times 10^{-3} \, M$$
$$+ 1·951 \times 10^{-4} \, TM \qquad (12)$$

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 comparision, 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.

<div style="display:flex">

Table 1
Specific heat of borage seeds in kJ kg^{-1} K^{-1}

Moisture content, % w.b.	Specific heat, kJ kg^{-1} K^{-1}		Difference, %[‡]
	Measured[*]	Estimated[†]	
Temperature at 6°C			
4·4	0·79	0·78	1·94
9·3	0·96	0·95	1·26
14·1	1·13	1·13	0
20·2	1·34	1·35	0·92
29·9	1·71	1·73	0·87
Temperature at 10°C			
4·4	0·82	0·81	0·65
9·3	1·04	1	4·13
14·1	1·2	1·18	1·91
20·2	1·42 +	1·41	0·23
29·9	1·79	1·78	0·75
Temperature at 20°C			
1·2	0·77	0·76	1·24
6·7	1·07[§]	1·00	6·89
9·3	1·14	1·10	2·83
15·6	1·31[§]	1·36	3·66
30·3	1·99[§]	1·91	3·86

[*]Average of three replicates (SD less than 0·05).
[†]Estimated using Eqn (13).
[‡]Equal to: 100[(measured−estimated)/measured].
[§]Data quoted from Yang *et al.* (1997).

The data for c_p obtained in this study were also used to verify the model developed by Yang *et al.* (1997), that is

$$c_p = 0.58 + 7.36 \times 10^{-3}T - 4.11 \times 10^{-5}T^2 + 3.04$$
$$\times 10^{-2}M + 1.81 \times 10^{-4}M^2 + 6.40 \times 10^{-4}TM$$
$$- 1.49 \times 10^{-5}TM^2 \qquad (13)$$

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 α 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:

$$\rho = 457.5 - 0.86M + 4.43 \times 10^{-2}M^2 \qquad (14)$$

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

Table 2
Bulk density of borage seeds

Moisture content, % w.b.	Bulk density, kg m^{-3}	SD
1·2	456·6	0·9
4·4	454·7	2·1
6·7	453·8	1·1
9·3	453·1	0·8
14·1	454·5	1·7
15·6	454·9	1·5
20·2	458·2	1·3
30·3	472·1	2·3

6, 10 and 20°C, respectively. The values for α ranged from 2.32×10^{-7} to 3.18×10^{-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 $(1.47 \times 10^{-7}$ m^2 s$^{-1})$ and air $(2.35 \times 10^{-5}$ m^2 s$^{-1})$ (Jiang *et al.*, 1986). In general, values for α 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 α and M have been reported. This is because the magnitude of α depends on the combined effects of k, ρ 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 ρ 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 α as a result of the uncertainties in those for k, ρ 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 devidation of k, ρ and c_p and the resultant α were obtained from statistical analysis of the experimental data and are summarized in Table 3. The calculated values of α were 3.18×10^{-7} $\pm 5.19 \times 10^{-8}$ m^2 s^{-1} for 1·2% w.b. moisture content and $2.93 \times 10^{-7} \pm 4.39 \times 10^{-8}$ m^2 s^{-1} for 30·3% w.b. moisture content (Table 3). These corresponded to a standard deviation of 2.59×10^{-8} and 2.19×10^{-8} m^2 s^{-1} and the coefficient of variation of 8·1 and 4·4 for α 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
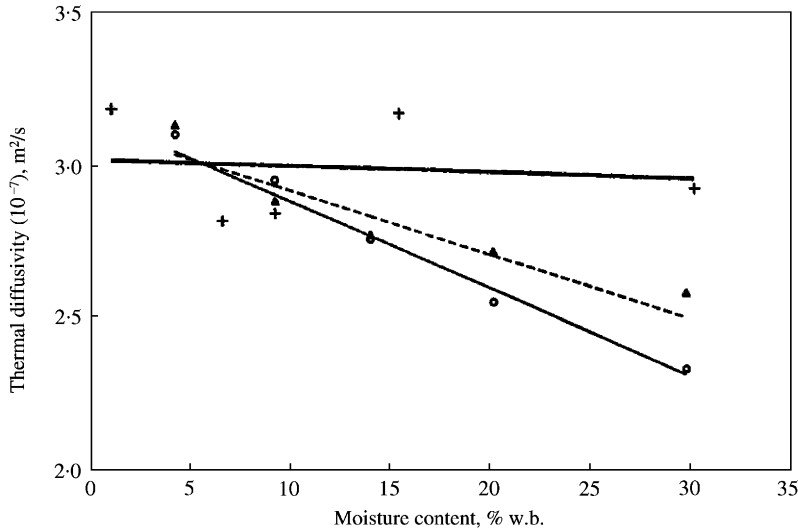
</div>

Fig. 5. Thermal diffusivities calculated by Eqn (10) and estimated by a multiple regression model from Eqn (15), respectively; ○, calculated for 6°C; ▲, calculated for 10°C; ✚, calculated for 20°C; ——, estimated for 6°C; ----, estimated for 10°C; ━━, estimated for 20°C

which was, in turn, about an order of magnitude larger than the contribution of the variation in the measured value of ρ.

Similar to the data for k, the calculated values of α 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 α versus M and T is

$$\alpha = (3\cdot24 - 1\cdot11 \times 10^{-2}T - 4\cdot044 \times 10^{-2}M + 1\cdot92 \times 10^{-3}TM) \times 10^{-7} \quad (15)$$

The values for α estimated by Eqn (15) are also shown in Fig. 5 in comparison with the values for α calculated by Eqn (1). It seemed from *Fig. 5* that Eqn (15) fit the values of α 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 α.

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

Moisture content, % w.b.	Thermal conductivity, $W\,m^{-1}\,K^{-1}$		Density, $kg\,m^{-3}$		Specific heat, $kJ\,kg^{-1}\,K^{-1}$	
	Mean	95% confidence limit	Mean	95% confidence limit	Mean	95% confidence limit
1·2	0·112	0·018	456·6	1·88	0·77	0·02
30·3	0·275	0·04	472·1	4·56	1·99	0·07

	Thermal diffusivity, $m^2\,s^{-1}$			
Moisture content %w.b.	Mean	95% confidence limit	SD	Coefficient of variation
1·2	$3\cdot18 \times 10^{-7}$	$5\cdot19 \times 10^{-8}$	$2\cdot59 \times 10^{-8}$	8·1
30·3	$2\cdot93 \times 10^{-7}$	$4\cdot39 \times 10^{-8}$	$2\cdot19 \times 10^{-8}$	4·4

dence level). 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 × 10^{-7} to 3·18 × 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 conetnet. Uncertainty analysis revealed that the variations in the thermal conductivity contributed mostly to uncertainty in the thermal diffusivity.

References

ASAE (2001). ASAE Standards. D243.3: Thermal Properties of Grain and Grain Products. ASAE, St. Joseph, MI

Asher G B; Sloan E D; Graboski M S (1986). A computer-controlled transient needle-probe thermal conductivity instrument for liquids. International Journal of Thermophysics, **7**, 285

Dickerson R W (1965). An apparatus for measurement of thermal diffusivity of foods. Food Technology, **19**(5), 198–204

Dutta S K; Nema V K; Bhardwaj R K (1988). Thermal properties of gram. Journal of Agricultural Engineering Research, **39**, 269–275

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

Huggins L F (1983). Analysis and interpretation. In: Instrumentation and Measurement for Environmental Sciences (Mitchell B W, ed.), p 15–02. ASAE, St. Joseph, MI

Jiang S; Jofriet J C; Mittal G S (1986). Thermal properties of haylage. Transactions of the ASAE, **29**, 601–606

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

Mohsenin N N (1980). Thermal Properties of Foods and Agricultural Materials. pp 83–121, Gordon and Breach, New York

Murakami E G; Okos M R (1988). Measurement and prediction of thermal properties of foods. In: Food Properties and Computer-Aided Engineering of Food Processing Systems (Singh P R; Medina A G, eds), p 3. Kluwer Academic, Boston

Neter J; Wasserman W; Kutner M H (1985). Applied Linear Statistical Models, p 289. Richard D. Irwin, Inc., Homewood, IL

Polley S I; Synder O P; Kotnour F (1980). A compilation of thermal properties of foods. Food Technology, **34**(11), 76–78

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

Sweat V E (1986). Thermal properties of foods. In: Engineering Properties of Foods (Rao M A; Rizvi S S H, eds), p 49. Marcel Dekker, New York

Tang J; Sokhansanj S; Yannacopoulos S; Kasap S O (1991). Specific heat of lentils by differential scanning calorimetry. Transactions of the ASAE, **34**, 517–522

Van der Held E F M; Van Drunen F G (1949). A method of measuring the thermal conductivity of liquids. Physica A, **15**, 865

Wang J; Hayakawa K (1993). Maximum slope method for evaluating thermal conductivity probe data. Journal of Food Science, **58**, 1340–1345

Yang W; Cenkowski S (1994). Enhancement of the Halsey equation for canola isotherms. Canadian Agricultural Engineering, **37**(3), 169–182

Yang W; Sokhansanj S; Tabil L Jr; Tang J; Yannacopoulos S (1997). Specific heat measurement for borage seeds by differential scanning calorimetry. Journal of Food Processing and Preservation, **21**, 395–407