Bulk thermal properties of alfalfa pellets

O.O. FASINA and S. SOKHANSANJ

Department of Agricultural and Bioresource Engineering, University of Saskatchewan, Saskatoon, SK, Canada S7N 5A9.
Received 3 March 1994; accepted 7 February 1995.

Fasina, O.O. and Sokhansanj, S. 1995. **Bulk thermal properties of alfalfa pellets.** Can. Agric. Eng. **37**:091-095. The line heat source method was used to obtain bulk thermal conductivity and thermal diffusivity of alfalfa pellets of moisture contents ranging from 7.5% to 18.0% (wet basis). Specific heat of the pellets was calculated from values of thermal conductivity, thermal diffusivity, and bulk density. Bulk thermal conductivity and thermal diffusivity of alfalfa pellets ranged from 0.112 to 0.204 $W \bullet m^{-1} \bullet K^{-1}$ and from 1.05×10^{-7} to 2.50×10^{-7} m^2/s respectively. Specific heat of the pellets varied from 1636 to 2021 $J \bullet kg^{-1} \bullet K^{-1}$. The thermal properties were not significantly affected by alfalfa pellet type.

La méthode de source de chaleur sur une ligne a été utilisée pour obtenir la conductivité thermique et la diffusivité thermique dans des tas de boulettes de luzerne dont les teneurs en eau variaient de 7.5% a 18.0% (base mouillée). La chaleur spécifique des boulettes a été calculée à partir des valeurs de conductivité thermique, diffusivité thermique et densité apparente. La conductivité thermique et la diffusivité thermique globale des boulettes de luzerne ont respectivement varié de 0.112 a 0.204 $W \bullet m^{-1} \bullet K^{-1}$ et de 1.05×10^{-7} à 2.50×10^{-7} m/s. La chaleur spécifique des boulettes a varié de 1636 a 2021 $J \bullet kg^{-1} \bullet K^{-1}$. Les propriétés thermiques n'ont pas été affectées de façon significative par le type de boulettes de luzerne.

INTRODUCTION

Alfalfa is pelleted to improve its storability, utilization, and handling. Pellets produced from freshly cut and hot-air dried alfalfa are called "dehy" pellets, while those from wilted and hot air-dried alfalfa are called "suncure" pellets. Pellets are made by grinding alfalfa and forcing the ground alfalfa through dies to from pellets ranging in diameter from 4 mm to 12 mm or even larger. After extrusion, the pellets are cooled before being placed in storage. Also, stored pellets are ventilated occasionally to prevent spoilage. Knowledge of the thermal properties (specific heat, thermal conductivity, and thermal diffusivity) of the pellets is therefore needed in the efficient design of pellet cooler and the selection of ventilating and cooling equipment.

Studies have been reported on the thermal properties of baled alfalfa (Bern 1964), alfalfa stem (Ott and Hurburt 1964), and baled alfalfa (Ford and Bilanski 1969). Jasansky and Bilanski (1973) found that the thermal conductivity of soybeans decreased with increase in particle size. Pelleting of alfalfa might have changed the thermal properties of ground alfalfa. This study was carried out to determine the moisture dependent specific heat, thermal conductivity, and thermal diffusivity of alfalfa pellets.

REVIEW OF THERMAL PROPERTIES MEASUREMENT

Most researchers have used the method of mixtures to experimentally determine the specific heat of biological products (Sharma and Thompson 1973; Mohsenin 1980; Dutta et al. 1988). This method involves placing the material in a heated water calorimeter and monitoring the temperature of the water until an equilibrium is reached. Specific heat of the material is calculated from the energy balance equation between the material and the heated water. This method assumes that moisture uptake by the material will be negligible during the process of heat transfer.

The method of mixtures is not effective for alfalfa pellets since a previous study (Fasina and Sokhansanj 1992) showed that alfalfa pellets are highly hygroscopic. In this study, specific heat of alfalfa pellets was calculated from measured values of thermal conductivity and thermal diffusivity as given in the relationship:

$$c = \frac{k}{\rho_b \alpha} \qquad (1)$$

where:

c = specific heat ($J \bullet kg^{-1} \bullet K^{-1}$),
k = thermal conductivity ($W \bullet m^{-1} \bullet K^{-1}$),
ρ_b = bulk density (kg/m^3), and
α = thermal diffusivity (m^2/s)

Equation 1 was used by Suter et al. (1975) and Moysey et al. (1977) to determine the specific heat of peanuts parts (pods, hulls, and kernels) and rapeseed, respectively.

The line heat source technique is mostly used to determine the thermal conductivity and thermal diffusivity of granular materials. This method, which is a transient method, is advantageous over the steady state methods of determining thermal conductivity because of the short duration of experiment (Reidy and Rippen 1971).

The line heat source technique involves applying a steady heat flux to the specimen and measuring the temperature rise at some point in the specimen resulting from the applied heat. When heat is applied by a small diameter wire imbedded in an infinite homogenous cylinder, temperatures will develop according to:

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

where:

T = temperature (K),
r = radial distance from line heat source (m), and
t = time (s).

The solution to Eq. 2, for the known temperature along the line source, is given by (Ingersoll et al. 1954) as:

$$T = \frac{Q}{2\pi k} \int_{\beta}^{\infty} \frac{\exp(-x^2)}{x} dx \quad (3)$$

where:

$$\beta = \frac{r}{2\sqrt{\alpha\theta}} \quad (4)$$

where:
Q = line heat source strength (W/m), and
θ = elapsed time (s).

Hooper and Lepper (1950) expanded Eq. 3 into a series solution to obtain:

$$T = \frac{Q}{2\pi k}\left(-\frac{E_c}{2} - \mathrm{Ln}(\beta) - \sum_{n=1}^{\infty} \frac{(-1)^n (\beta^2)^n}{2n\, n!}\right) \quad (5)$$

where:
E_c = Euler's constant (0.5772157).

For values of $\beta < 0.16$, the exponential integral of Eq. 5 is approximated, with less than 1% error (Ingersoll et al. 1954), by:

$$T = \frac{Q}{2\pi k}\left(\mathrm{Ln}\frac{1}{\beta} - \frac{r}{2}\right) \quad (6)$$

This condition is satisfied if Eq. 5 is evaluated at a point close to the line source. Between times θ_1 and θ_2, the temperature change is therefore given by:

$$T_2 - T_1 = \frac{Q}{4\pi k} \mathrm{Ln}\frac{\theta_2}{\theta_1} \quad (7)$$

To compensate for the mass and size of the heating element, a time correction factor, θ_0, is subtracted from each observed time such that:

$$T_1 - T_1 = \frac{Q}{4\pi k} \mathrm{Ln}\frac{\theta_2 - \theta_0}{\theta_1 - \theta_0} \quad (8)$$

In this study, θ_0 was estimated by extrapolating the plot of $dT/d\theta$ against time at $dT/d\theta$ of zero. At $dT/d\theta = 0$, the average value of θ_0 was 6 s. Thermal conductivity was obtained from the slope ($Q/4\pi k$) of the plot of temperature difference ($T_2 - T_1$) against the natural logarithm of the corrected times (Eq. 8).

Nix et al. (1969) and Mohsenin (1980) showed that if an additional sensor is placed at a known distance, r, from the line source such that the condition, $0.5 < \beta < 2.5$, is satisfied over the time interval of each test, then the thermal conductivity apparatus can be used to determine thermal diffusivity.

The Newton-Ralphson iteration technique was used to obtain values of β that satisfy Eq. 5. With known distance from the line source, thermal conductivity obtained from Eq. 8 and the constant line heat source Q for each trial, a value of β was calculated for all the times at which data were obtained. The criterion used for optimizing the value of β was that the difference between the left hand side and right hand side of Eq. 5 should not be greater than 1×10^{-5}. Using Eq. 4, the computed average value of β was then used in calculating the value of thermal diffusivity for that trial.

MATERIALS AND METHODS

Figure 1 shows a schematic diagram of the apparatus used for the thermal conductivity and thermal diffusivity tests. A 152.4-mm diameter and 762.0-mm long PVC pipe was used as the sample container. The sample holder was insulated at the sides with 25 mm of fibre glass and at the ends with 100 mm of styrofoam. A 1.397-mm diameter chromel resistance heating wire (4.29 Ω/m) was stretched along the axis of the cylinder. A constant power of 1.1 W was applied to the heater wire from a DC power supply using a constant current of 0.69 A. The maximum variation in supplied power for all the experimental combinations was ±0.0105 W.

Temperature measurements were made with 0.25-mm diameter teflon coated copper-constantan thermocouple wires. One thermocouple wire was attached midway along the heater wire. The transient temperature measurements obtained from this thermocouple were used in the determination of thermal conductivity of the sample using Eq. 7. Two other thermocouples were inserted into the sample container from the sides such that the bead of the thermocouple was at a distance of 12.7 mm from the heater wire. Temperature outputs from these thermocouples were used in thermal diffusivity calculations (Eq. 4). The temperature history of the thermocouples and the current supplied to the heater were recorded on a computer via a 63 channel 8082A datalogger and an IBM PC 801 interface card (Sciemetric Instruments Inc., Manotick, ON). The recording time interval was 3 s.

Tests were conducted on 6.4 mm and 9.5 mm dehy, and 6.4 mm and 7.9 mm suncure (the figures are the nominal diameter of the pellets) alfalfa pellets obtained from commercial

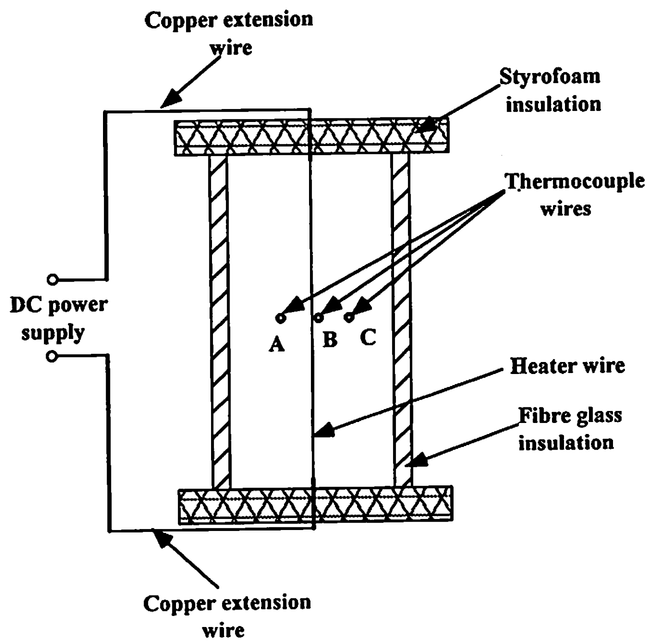

Fig. 1. Schematic diagram of test apparatus used to determine the thermal properties of alfalfa pellets.

producers in Western Canada. Samples were adjusted to desired moisture contents by placing them in a humidity chamber adjusted to a relative humidity of 90% and temperature of 30°C. Conditioned samples were allowed to equilibrate for a period of 24 h before each test. Moisture content of samples was determined according to the ASAE standard S358.2 (ASAE 1992) Four moisture contents between 7.5% and 18% (wet basis) were used for each pellet type. The initial moisture contents of the pellet samples were 7.5% for 6.4 mm dehy; 9.4% for 9.5 mm dehy; 10.0% for 6.4 mm suncure, and 7.7% for 7.5 mm suncure, all on a wet basis. The experimental data were based on three replications.

RESULTS AND DISCUSSION

Figure 2 shows a typical temperature profile in bulk 6.4 mm pellets. As expected, temperature values obtained from thermocouple B over time were exponential in nature with an initial lag period of about 6 s. Within a time duration of about 200 s, the temperature recorded by thermocouple B increased by about 9 to 10°C. Temperatures from thermocouples A and C also increased over time in more of a linear fashion. The maximum differences in readings between thermocouples A and C was less than 0.2°C. This difference was mostly due to the initial difference in temperatures recorded by the thermocouples at the start of the experiment. Both thermocouples experienced a temperature increase of 0.5°C over a duration of 200 s. The average values of thermocouples A and C were used in the analysis for determination of thermal diffusivity.

Tables I to III show the mean values and standard deviations of thermal conductivity, thermal diffusivity, and calculated specific heat (using Eq. 1) of the four types of alfalfa pellets used in the study. Thermal conductivity values

Table I. Mean thermal conductivity ($W \bullet m^{-1} \bullet K^{-1}$) and standard deviation of alfalfa pellets

Pellet type	Moisture content (% w.b.)	Percentage moisture increase (% w.b.)			
		0.0[a]	2.3	5.4	8.5
6.4 mm[b] dehy[c]	7.5	0.114 ±0.009	0.133 ±0.008	0.145 ±0.010	0.180 ±0.0012
6.4 mm[b] suncure[d]	10.0	0.131 ±0.007	0.144 ±0.007	0.181 ±0.011	0.201 ±0.012
9.5 mm[b] dehy[c]	9.8	0.134 ±0.008	0.142 ±0.005	0.182 ±0.010	0.204 ±0.009
7.5 mm[b] suncure[d]	7.7	0.112 ±0.008	0.135 ±0.009	0.142 ±0.007	0.179 ±0.008

[a]The value of 0.0 represents the moisture for each sample given in column 2
[b]Nominal diameter of pellets
[c]dehy refers to pellets made from freshly cut and hot air-dried alfalfa
[d]suncure refers to pellets made from wilted and hot air-dried alfalfa

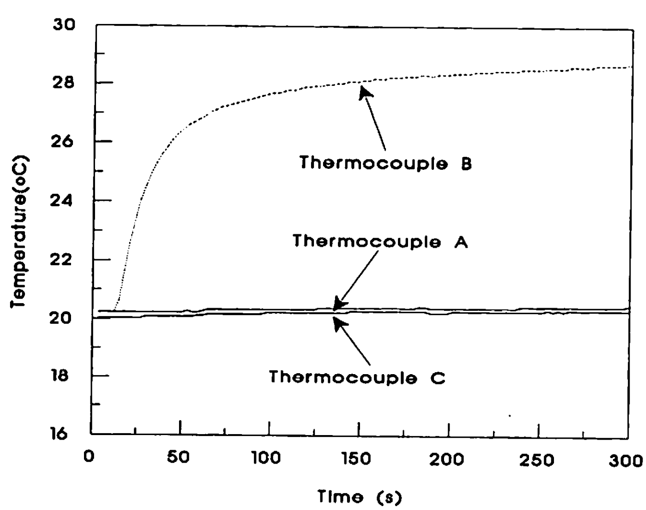

Fig. 2. Typical temperature profile in bulk pellets as measured by the thermocouples.

ranged from 0.112 to 0.204 $W \bullet m^{-1} \bullet K^{-1}$ within the moisture range of 7.5 to 18% (w.b.). Thermal diffusivity and specific heat of alfalfa pellets also increased with moisture content with a thermal diffusivity range of 1.05 x 10^{-7} to 2.50 x 10^{-7} m^2/s and specific heat range of 1636 to 2021 $J \bullet kg^{-1} \bullet K^{-1}$. The values of thermal properties of pelleted alfalfa obtained in this study are similar to those of ground alfalfa and baled alfalfa. Bern (1964) found that the specific heat values of ground alfalfa at moisture contents between 4.0 and 18% (w.b.) varied between 1176 and 2016 $J \bullet kg^{-1} \bullet K^{-1}$. A lower average thermal diffusivity value of 9.83 x 10^{-8} m^2/s was reported for alfalfa stems by Watts and Bilanski (1973). Within a density range of 192 to 336 kg/m^3, Ott and Hurburt (1964) measured the thermal diffusivity value of baled alfalfa to decrease from 3.612 x 10^{-7} to 1.54 x 10^{-7} m^2/s as bale density increased.

A test of significance (at 95% confidence level) showed that moisture had significant effect and pellet type did not have significant effect on specific heat, thermal conductivity, and thermal diffusivity values. Consequently, thermal conductivity and thermal diffusivity values for the different pellet types were lumped. A linear regression was performed using SAS statistical package (SAS 1986) and the resulting equations relating the thermal properties to moisture content are given below. A second order polynomial was found to best fit the dependence of specific heat of alfalfa pellets on moisture. It is suspected that this was because of the calculations done in Eq. 1 since the changes of thermal diffusivity, thermal conductivity, and bulk density of alfalfa pellets to moisture are not the same. Data on the moisture dependent bulk density of alfalfa pellets were obtained from a previous study (Fasina and Sokhansanj 1992) as given in Eq. 12. The degree of correlation of the fit of regression to experimental data was greater than 0.96.

$$k = 0.049 + 0.0082\,M \tag{9}$$

Table II. Mean thermal diffusivity (10^{-7} m^2/s) and standard deviation of alfalfa pellets

Pellet type	Moisture content (% w.b.)	Moisture change (% w.b.)			
		0.0[a]	2.3	5.4	8.5
6.4 mm[b] dehy[c]	7.5	1.06 ±0.20	1.15 ±0.14	1.25 ±0.21	1.50 ±0.15
6.4 mm[b] suncure[d]	10.0	1.14 ±0.13	1.24 ±0.20	1.51 ±0.12	1.72 ±0.20
9.5 mm[b] dehy[c]	9.8	1.13 ±0.18	1.24 ±0.14	1.51 ±0.11	1.73 ±0.12
7.5 mm[b] suncure[d]	7.7	1.06 ±0.09	1.16 ±0.12	1.24 ±0.10	1.49 ±0.11

[a]The value of 0.0 represents the moisture for each sample given in column 2
[b]Nominal diameter of pellets
[c]dehy refers to pellets made from freshly cut and hot air-dried alfalfa
[d]suncure refers to pellets made from wilted and hot air-dried alfalfa

Table III. Calculated mean specific heat ($J \bullet kg^{-1} \bullet K^{-1}$) and standard deviation of alfalfa pellets

Pellet type	Moisture content (% w.b.)	Moisture increase (% w.b.)			
		0.0[a]	2.3	5.4	8.5
6.4 mm[b] dehy[c]	7.5	1636 ±30	1789 ±23	1860 ±38	1998 ±21
6.4 mm[b] suncure[d]	10.0	1781 ±30	1849 ±24	1981 ±20	2008 ±36
9.5 mm[b] dehy[c]	9.8	1843 ±35	1806 ±28	1987 ±32	2021 ±39
7.5 mm[b] suncure[d]	7.7	1596 ±40	1804 ±35	1841 ±23	2005 ±33

[a]The value of 0.0 represents the moisture for each sample given in column 2
[b]Nominal diameter of pellets
[c]dehy refers to pellets made from freshly cut and hot air-dried alfalfa
[d]suncure refers to pellets made from wilted and hot air-dried alfalfa

$$\alpha = 0.53 \times 10^{-7} + 0.062 \times 10^{-7} M \quad (10)$$

$$c_b = 1083.23 + 89.638 M - 2.10 M^2 \quad (11)$$

$$\rho = 719.10 - 7.42 M \quad (12)$$

where M = moisture content (% wet basis).

CONCLUSIONS

From this study, the following conclusions can be made:

1) The thermal properties of pelleted alfalfa and ground alfalfa are similar.
2) The thermal properties of dehy alfalfa pellets are not significantly different from those of suncure alfalfa pellets.
3) The thermal conductivity of alfalfa pellets increases linearly with moisture content. The thermal conductivity ranged from 0.112 to 0.204 $W \bullet m^{-1} \bullet K^{-1}$ for a moisture content range of 7.5 to 18.0% (wet basis).
4) The thermal diffusivity of alfalfa pellets increases linearly with moisture content. The thermal diffusivity ranged from 1.05×10^{-7} to 2.50×10^{-7} m^2/s for a moisture content range of 7.5 to 18.0% (wet basis).
5) A polynomial relationship of the second order exists between specific heat of alfalfa pellets and moisture content with values ranging from 1636 to 2021 $J \bullet kg^{-1} \bullet K^{-1}$ for a moisture content range of 7.5 to 18.0% (wet basis).

REFERENCES

ASAE. 1992. Standard S358.2 - Moisture measurement - Forages. In *ASAE Standards 1992*, 406. St. Joseph, MI: ASAE.

Bern, C.J. 1964. The specific heat of alfalfa. Unpublished M.Sc thesis. University of Nebraska, Lincoln, Nebraska.

Dutta, S.K., V.K. Nema and R.J. Bhardwaj. 1988. Thermal properties of grain. *Journal of Agricultural Engineering Research* 39:269-275.

Fasina, O.O. and S. Sokhansanj. 1992. Hygroscopic moisture absorption by alfalfa cubes and pellets. *Transactions of the ASAE* 35(5):1615-1619.

Ford, R.M. and W.K. Bilanski. 1969. Thermal diffusivity of alfalfa stems. *Transactions of the ASAE* 12(2):249-251.

Hooper, F.C. and A.R. Lepper. 1950. Transient heat flow apparatus for the determination of thermal conductivity. *ASHVE Transactions* 56:309-324.

Ingersoll, L.R., O.J. Zobel and A.C. Ingersoll. 1954. *Heat Conduction with Engineering and Geological Applications*. New York, NY: McGraw Hill Publishers.

Jasansky, A. and W.K. Bilanski. 1973. Thermal conductivity of whole and ground soybeans. *Transactions of the ASAE* 16(1):100-103.

Mohsenin, N.N. 1980. *Thermal Properties of Food and Agricultural Materials*. New York, NY: Gordon and Breach Publishers.

Moysey, E.B., J.T. Shaw and W.P. Lampman. 1977. The effect of temperature and moisture on the thermal properties of rapeseed. *Transactions of the ASAE* 20(3):461-477.

Nix, G.H., R.J. Vachon, G.W. Lowery and I.A. McCurry. 1969. The line source method: procedure and iteration scheme for combined determination of conductivity and diffusivity. In *Proceedings of the 18th Conference in Thermal Conductivity*, eds. C.Y. Ho and R.E. Taylors, 999-1008. New York, NY: Plenum Press.

Ott, L.E. and L.W. Hurbut. 1964. Thermal diffusivity of compressed alfalfa hay. ASAE Paper No. 64-817. St. Joseph, MI: ASAE.

Reidy, G.A. and A.L. Rippen 1971. Methods for determining thermal conductivity in foods. *Transactions of the ASAE* 14(2):248-254.

SAS. 1986. *SAS User's Guide: Statistics*. Cary, NC: Statistical Analysis System Institute Inc.

Sharma, D.K. and T.L. Thompson. 1973. Specific heat and thermal conductivity of sorghum. *Transactions of the ASAE* 16(1):114-117.

Suter, D.A., K.K. Agarwal and B.L. Clary. 1975. Thermal properties of peanut pods, hulls and kernels. *Transactions of the ASAE* 18(2):370-375.

Watts, K.C. and W.K. Bilanski. 1973. Methods for estimating the thermal diffusivity of whole soybeans. *Transactions of the ASAE* 16(5):1143-1145.