Thermal conductivity and thermal diffusivity of timothy hay

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Opoku, A., Tabil, L.G., Crerar, B. and Shaw, M.D. 2006. **Thermal conductivity and thermal diffusivity of timothy hay**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **48**: 3.1 - 3.7. To predict moisture and temperature distributions within baled hay during storage, drying, heating, and cooling, thermal properties such as specific heat, thermal conductivity, and thermal diffusivity may be required in mathematical modeling and the simulation process. A dual thermal probe consisting of a thermal conductivity probe and thermal diffusivity probe was used to determine the thermal properties of timothy hay at different moisture contents (7.7, 14.4, and 17.1% w.b.), initial temperatures (-17.8, -5.2, 5.16, 23.6, and 60.1°C) and bulk densities on wet basis (110, 184, and 275 kg/m^3). The mean thermal conductivity of timothy hay ranged from 0.0284 to 0.0605 W m^{-1} °C^{-1}. The thermal conductivity values increased with increasing temperature, moisture content, and bulk density. A multiple regression model was developed to predict the thermal conductivity of the timothy hay using initial hay temperature, moisture content, and bulk density. The model is valid within the limits of the parameters used in the experiments. The mean thermal diffusivity of the timothy hay ranged from1.042 x 10^{-7} to 3.031 x 10^{-7} m^2/s. There were little or no linear relationships between thermal diffusivity and initial temperature, moisture content, and bulk density of timothy hay. **Keywords**: dual thermal probe, line heat source, timothy hay, thermal properties.

La modélisation de la distribution de la teneur en eau et de la température à l'intérieur de balles de foin durant l'entreposage, le séchage, le chauffage et le refroidissement fait appel aux propriétés thermiques de ces fourrages telles que la chaleur spécifique, la conductivité thermique et la diffusivité thermique pour la simulation mathématique des processus de transfert de chaleur et de matière. Une sonde thermale comportant des senseurs de conductivité et de diffusivité thermiques a été utilisée pour déterminer les propriétés thermiques de la phléole à différentes teneurs en eau (7,7, 14,4 et 17,1% b.h.), températures initiales (-17,8, -5,2, 5,16, 23,6 et 60,1ºC) et masses volumiques sur base humide (110, 184 et 275 kg/m^3). Il a été observé que la conductivité thermique moyenne de la phléole variait de 0,0284 à 0,0605 W m^{-1} ºC^{-1}. Les valeurs de conductivité thermique augmentaient avec l'augmentation de la température, de la teneur en eau et de la masse volumique. Un modèle de régression multiple a été développé pour prédire la conductivité thermique de la phléole en utilisant la température initiale du fourrage, sa teneur en eau et sa masse volumique. Le modèle est précis à l'intérieur des valeurs de ces différents paramètres utilisés lors de l'expérimentation. La diffusivité thermique moyenne de la phléole variait de 1,042 x 10^{-7} à 3,031 x 10^{-7} m^2/s. Il n'y avait cependant pas de relation linéaire entre la diffusivité thermique et la température initiale, la teneur en eau et la masse volumique de la phléole. **Mots clés**: sonde thermale, source de chaleur linéaire, phléole, propriétés thermiques.

INTRODUCTION

Timothy (*Phleum pratense*) hay is an excellent source of fiber for livestock and its palatability encourages higher levels of intake by animals. Timothy hay is cut and allowed to dry in the field before baling. The rate of field drying may be dependent on environmental conditions, plant maturity, and density of the hay in a swath or windrow. Due to these factors, field drying of the hay to safe storage moisture contents of 10 to 12% wet basis (w.b.) may be unnecessarily prolonged.

Prolonged field drying may lead to unacceptable losses and quality reduction of the product. Hay quality reduction can lead to economic loss to farmers and processors. Hay processors in Western Canada have expressed the desire to bale timothy hay at higher moisture content into large square bales (1.2 x 1.2 x 2.4 m) and artificially dry them to reduce the long field drying time and the consequent risk of encountering inclement weather during field drying, thus improving hay quality.

A processor has recently developed a new dryer for drying large square bales. The dryer was tested for moisture and temperature distribution during the drying of large timothy hay bales (Crerar et al. 2004). To improve the dryer design and to predict moisture and temperature distribution within the bale, thermal properties of the baled hay may be required in mathematical modeling and simulation of the drying process (Chang and Johnson 1971; Drouzas et al. 1991; Kostaropoulos and Saravacos 1997; Istadi and Sitompul 2002). Mathematical modeling provides an effective means to simulate heat and mass transfer during the drying process. To select a suitable mathematical model for drying, thermal properties such as thermal conductivity and diffusivity may be required to calculate heat transfer Biot and Fourier numbers (Parti 1993). Chua et al. (2002) used thermal properties such as thermal conductivity and specific heat capacity to model the temperature and moisture distribution in potato slices during convective drying.

Thermal properties have been used to model the cooling and heating of agricultural food products (Fasina and Sokhansanj 1995; Xu and Burfoot 1999; Tang et al. 2000; Wang et al. 2001) The determination of thermal properties of timothy hay may help in the modeling and designing of appropriate equipment for heating and cooling of hay during thermal disinfestation of the product of insect pests such as Hessian fly (*Mayetiola destructor* (Say)).

Different methods (steady and non-steady states) for measuring thermal conductivity and diffusivity of food and biological materials are described in the literature (Mohsenin 1980; Nesvadba 1982). The heated probe method is based on the line heat source, a non-steady state method. It has become

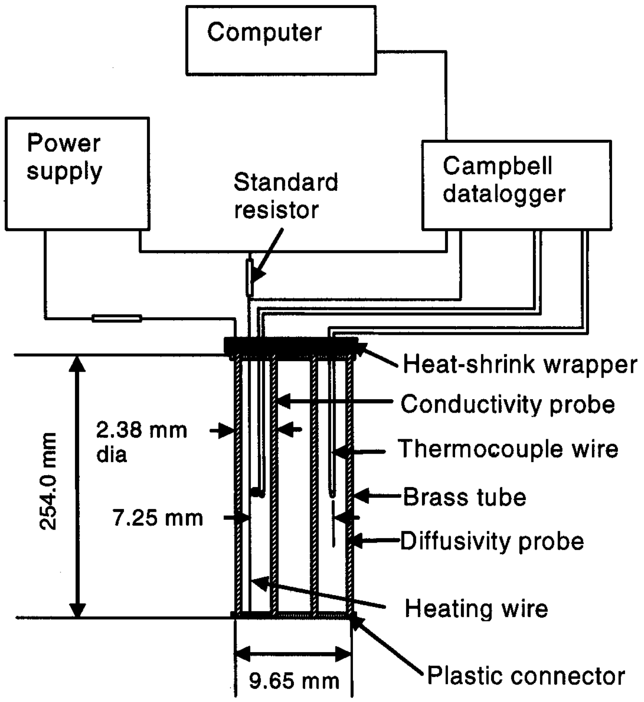

Fig. 1. Experimental setup used to determine the thermal properties of timothy hay.

a commonly acceptable method to researchers in determining the thermal conductivity and diffusivity of food and biological materials compared to the steady state method, since it eliminates moisture loss and moisture migration within the material. The heated probe method is rapid and applicable to most food and biological materials.

The thermal conductivity probe was initially developed by Hooper and Lepper (1950). In the heated probe method, a constant heat source is applied to the probe which is embedded in a uniform temperature medium whose thermal conductivity is to be determined. The temperature at the center of the probe is measured and a slope is determined from a plot of temperature rise and natural logarithm of time.

Nix et al. (1967, 1969) demonstrated that the thermal conductivity probe apparatus could be utilized to simultaneously determine the thermal diffusivity directly when an additional temperature sensor was placed at a known distance from the thermal conductivity probe in the medium. This technique has been successfully used to simultaneously determine the thermal conductivity and diffusivity of peanut pods, hulls, and kernels (Suter et al. 1975), rapeseed (Moysey et al. 1977), tomato juice concentrates (Choi and Okos 1983), rice bran (Sreenarayanan and Chattopadhyay 1986), granular starch (Drouzas et al. 1991), and organic waste (Iwabuchi et al. 1999). Casada and Walton (1989a, 1989b) employed the additional temperature sensor to simultaneously determine the thermal conductivity and diffusivity of baled burley tobacco.

The objective of this research was to determine the thermal properties of timothy hay, specifically, thermal conductivity, and thermal diffusivity in order to design or select an appropriate dryer or a thermal treatment unit. The effects of hay moisture content, initial temperature, and bulk density on thermal properties were also determined.

MATERIALS and METHODS

Materials

Baled timothy hay was obtained from Elcan Forage Inc., Broderick, Saskatchewan. The timothy hay was from the fall 2003 harvest. The timothy hay had an initial moisture content of 10.3% w.b. and bulk density on wet basis of 161.1 kg/m^3. The dimensions of the baled hay were (length, width, and height) 2.34, 1.30, and 1.18 m, respectively. The hay was cut into pieces and fluffed before conditioning to ensure uniform moisture distribution. For the lower moisture content (7.7% w.b.), the hay was dried at 70.0°C in a laboratory built forced-air dryer for about 30 min. For the higher moisture contents (14.4 and 17.1% w.b.), the hay was conditioned by spraying a required amount of distilled water and the conditioned hay was stored at a temperature of 5.0°C and relative humidity of 80% for at least one week in a walk-in cooler. The moisture contents of the conditioned hay were determined using the oven method.

Thermal conductivity and diffusivity determination

Experimental apparatus A dual thermal probe was constructed from hollow brass tubes. Each tube had an outer diameter of 2.38 mm and length of 254.0 mm (Fig. 1). The dual probe consisted of a thermal conductivity probe and a thermal diffusivity probe mounted parallel to each other. The centers of the conductivity and the diffusivity probes were spaced about 7.25 mm from each other. The spacing was determined by a digital caliper. An insulated constantan heating wire (0.38 mm diameter) and insulated constantan-copper thermocouple wire (0.25 mm diameter) were inserted into the brass tube. The thermocouple wire was glued to the heating wire and the temperature rise was measured midway along the conductivity probe. A constantan-copper thermocouple wire (0.25 mm diameter) was inserted inside the thermal diffusivity probe and the temperature rise was measured midway along the probe. The wires were coated with a high thermal conductivity paste (Thermal compound Part No. 120-8, Wakefield Engineering Inc., Wakefield, MA) before inserting them inside the hollow brass tubes. The paste is stable within the temperature range of -40.0 to 200.0°C. The constantan heating wire was soldered to the brass tube at one tip and epoxy glue was used to seal the end. Lead wires were connected to the heating wire and the thermocouple wires and heat-shrink wrappers were applied to cover the bare wires. A lead wire was soldered to the conductivity probe shaft at the base of the handle. All the wires and the upper tip of the probe were covered with a heat-shrink wrap to act as a handle, and to strengthen and protect the wires. The conductivity and the diffusivity probes were inserted through holes made in small plastic connectors to keep them parallel. Epoxy glue was used to bond the conductivity and diffusivity probes to the plastic connectors. Two dual thermal probes were constructed.

The heating wires were connected to a power supply (Model 25-29, Anatek Electronics Ltd., Vancouver, BC), which supplied a constant voltage by connecting a resistor in series with the heating wires. The current through the heating wire was determined using Ohm's law, by measuring the voltage across a standard resistor. The temperatures and the current through the heating wire were recorded by a datalogger (Model CR10X, Campbell Scientific Inc., Logan, UT) connected to a computer. The data were measured and recorded at one-second intervals.

A metal compression box having a length of 305 mm, width of 203 mm, and a height of 203 mm was constructed. Four C-clamps were welded to the sides of the box to compress and hold the hay at a required bulk density. Holes were drilled on one side of the box for the dual thermal probe insertion. The probes were inserted along the length (305 mm) of the box. Five compression boxes were constructed.

Experimental procedure The dual probes were used to determine the thermal properties of distilled water mixed with agar at room temperature. Agar solution, 1.0% by mass, was prepared. The thermal properties of the solution were also determined by using the KDS thermal properties analyzer (Decagon Devices, Inc., Pullman, WA) in order to compare the accuracy and precision of the dual probes. The thermal properties analyzer has a needle length and diameter of 60 and 0.9 mm, respectively. Its accuracy for measuring thermal conductivity is 5% and that of thermal diffusivity is 10%.

A known mass of timothy hay was randomly placed in each of the compression boxes and compressed to a desired bulk density. The boxes containing the hay were placed at different temperature environments to equilibrate. A pointed, circular rod was used to make holes in the compressed hay before the dual thermal probe was inserted. After probe insertion, it was allowed to reach constant temperature with the hay. At equilibrium, the power supply was turned on and a constant voltage of approximately 20.0 V d.c. was supplied to the heating wires. Each test was run for approximately 300 s during which the temperatures and the current were logged every second. Three replications were conducted at each bulk density on wet basis (110, 184, and 275 kg/m^3), mean temperature of the environments (-17.8, -5.2, 5.2, 23.6, and 60.1°C) and moisture content (7.7, 14.4, and 17.1% w.b.) combinations. Experiments for low density (110 kg/m^3) and high moisture content (17.1%) for different temperatures were not conducted due to time and experimental constraints.

Data analysis Microsoft Excel (Microsoft Corp., Redmond, WA) was used to analyze the results. The slope (S) and the coefficient of determination (R^2) were determined successively for each experimental run using data intervals of 41, 51, and 61. The slope for the highest R^2 was selected from the data intervals and used in the thermal conductivity determination (Murakami and Okos 1988; Casada and Walton 1989). Slopes with R^2 values of less than 0.9990 were not used in the thermal conductivity determination (Sweat 1995). The thermal conductivity was determined from Eq. 1.

$$k = \frac{I^2 R}{4\pi S} \tag{1}$$

where:

k = thermal conductivity (W m^{-1} °C^{-1})

I = current (A),

R = specific resistance of the heating wire (Ω/m), and

S = slope determined from the data points (°C).

Nix et al. (1967) gave Eq. 2 for the estimation of thermal diffusivity when an additional thermocouple sensor was placed at a known distance from the conductivity probe:

$$\Delta T = \frac{I^2 R}{2\pi k}\left(-\frac{C_e}{2} - \ln\beta + \frac{\beta^2}{2*1!} - \frac{\beta^4}{4*2!} + \ldots\ldots\right) \tag{2}$$

where:

ΔT = temperature rise measured using the additional temperature sensor (°C),

C_e = Euler's constant (0.5772157),

β = $0.5r(\alpha t)^{-0.5}$ (dimensionless),

r = radial distance between conductivity and diffusivity probes (m),

t = heating time (s), and

α = thermal diffusivity (m^2/s).

Data points from 60 to 200 s during heating were used to calculate the thermal diffusivity of the hay material. β was determined at each data point from the heating time, the measured distance, and an assumed value of the thermal diffusivity. The temperature rise at that data point was then calculated and subtracted from the measured temperature. The differences between the measured and the calculated values for all the data points were summed. Goal Seek, a program in Microsoft Excel, was used to set the sum to zero by changing the thermal diffusivity value. The final value was used as the estimated thermal diffusivity for that test.

Statistical analysis was performed on the results using SPSS for Windows, Version 11.5.0. (SPSS Inc., Chicago, IL). Analysis of variance, correlation coefficients (r), and multiple regression analysis were conducted on the thermal conductivity and thermal diffusivity as a function of initial hay temperature, moisture content, and bulk density.

Moisture content determination

The moisture content of the timothy hay was determined using the oven method according to the ASAE Standard S358.2 (ASAE 2003). Approximately 25 g of the hay was placed in a container and covered with perforated aluminum foil to prevent the loss of material during drying. The containers were placed in an oven at a temperature of 103±1°C for 24 h. The initial and final masses were measured using a weighing scale. The moisture content of the hay in wet basis (w.b.) was calculated from the initial and the final masses.

RESULTS and DISCUSSION

Tables 1 and 2 show the thermal properties of 1% agar solution determined with the KDS thermal properties analyzer and the two dual probes. The mean thermal conductivity values for the KDS analyzer, dual probe 1, and dual probe 2 were 0.606, 0.607, and 0.608 W m^{-1} °C^{-1}, respectively. The mean thermal diffusivity values for the two dual probes were slightly higher than the value for the KDS. The two dual probes had higher standard deviation and coefficient of variation values compared to the KDS analyzer. Dual probe 1 had the highest standard deviation and coefficient of variation values. There was no statistical difference between the mean thermal conductivity values measured by the three probes at the 5% level of significance using Tukey's multiple comparison procedure. The mean thermal diffusivity values determined using the three

Table 1. Thermal conductivity values of 1% agar solution using different probes.

	KDS Analyzer		Dual Probe 1		Dual Probe 2	
	Initial temperature (°C)	Thermal conductivity ($W\ m^{-1}\ °C^{-1}$)	Initial temperature (°C)	Thermal conductivity ($W\ m^{-1}\ °C^{-1}$)	Initial temperature (°C)	Thermal conductivity ($W\ m^{-1}\ °C^{-1}$)
	24.2	0.620	22.9	0.578	22.6	0.582
	23.7	0.590	22.9	0.619	22.5	0.618
	23.7	0.610	23.1	0.626	22.7	0.623
Mean	23.9a*	0.606a	23.0b	0.607a	22.6b	0.608a
SD	0.3	0.015	0.1	0.026	0.1	0.022
CV(%)	-	2.52	-	4.24	-	3.66

* Means, for a particular parameter, with the same letter are not significantly different at the 5% level of significance.

Table 2. Thermal diffusivity values of 1% agar solution using different probes.

	KDS Analyzer		Dual Probe 1		Dual Probe 2	
	Initial temperature (°C)	Thermal diffusivity ($10^{-7}\ m^2/s$)	Initial temperature (°C)	Thermal diffusivity ($10^{-7}\ m^2/s$)	Initial temperature (°C)	Thermal diffusivity ($10^{-7}\ m^2/s$)
	24.2	1.500	22.9	1.427	22.6	1.986
	23.7	1.400	22.9	1.320	22.5	1.675
	23.7	1.400	23.1	1.769	22.7	1.896
Mean	23.9a*	1.433a	23.0b	1.505a	22.6b	1.852a
SD	0.3	0.058	0.1	0.235	0.1	0.160
CV(%)	-	4.02	-	15.57	-	8.64

* Means, for a particular parameter, with the same letter are not significantly different at the 5% level of significance.

probes did not differ significantly at the 5% level. Also, at 1% significance level the conductivity and diffusivity values obtained using the three probes did not differ from each other. The dual probes were less precise in measuring the thermal conductivity and diffusivity values. Rahman (1995) reported the thermal conductivity of water as 0.608 $W\ m^{-1}\ °C^{-1}$ at a temperature of 25.0°C. The thermal diffusivity of water at a temperature of 25.0°C was calculated to be $1.462 \times 10^{-7}\ m^2/s$.

The thermal properties analyzer had higher repeatability compared to the probes used in this investigation. The method and the mathematical model for estimating the thermal diffusivity differ for the dual probes and the analyzer. The thermal analyzer uses a single probe for determining thermal conductivity and diffusivity, whereas the dual probes use two parallel probes. The analyzer ignored higher order terms when calculating the thermal diffusivity whereas higher order terms up to 30 were used for the dual probes. The variability in the diffusivity values determined by the dual probes could probably be attributed to natural convection currents that affected the diffusivity probe. The high thermal diffusivity values given by probe 2 could be attributed to the imprecise construction and measurement of the distance between the centers of the conductivity and the diffusivity probes. Statistically, there were no differences in the thermal conductivity and diffusivity values determined by the thermal analyzer and the dual probes. Casada and Walton (1989a) developed a new model for predicting thermal diffusivity of tobacco. The model predicted mostly higher diffusivity values compared to the model used in this experiment. Casada and Walton's new model was not used in the estimation of diffusivity values in this experiment.

Thermal conductivity of timothy hay

The thermal conductivity of the timothy hay at different temperatures, moisture contents, and bulk densities are shown in Table 3. Figure 2 shows a typical temperature rise in the compressed hay for the determination of thermal conductivity and diffusivity. The thermal conductivity of the timothy hay ranged from 0.0284 to 0.0605 $W\ m^{-1}\ °C^{-1}$. The lowest thermal conductivity was obtained at a mean temperature of -17.8°C, moisture content of 7.7% w.b., and bulk density of 110 kg/m^3. The highest value was obtained at a mean temperature of 60.1°C, moisture content of 17.1% w.b., and bulk density of 184 kg/m^3. The thermal conductivity values increased with increasing initial temperature ($r = 0.770$), moisture content ($r = 0.343$), and bulk density ($r = 0.471$). Statistical analysis indicated that initial temperature, moisture content, and bulk density had significant effect on the thermal conductivity values at a 5% significance level. Casada and Walton (1989b) determined the thermal conductivity of burley tobacco leaf at

Table 3. Thermal conductivities and thermal diffusivities of timothy hay at various temperatures, moisture contents, and bulk densities.

Initial mean hay temperature (°C)	Moisture content of hay (% w.b.)	Bulk density (kg/m^3)	Thermal conductivity* (W m^{-1} °C^{-1})	Thermal diffusivity* (10^{-7} m^2/s)
-17.8	7.7	110	0.0284	1.229
-5.2	7.7	110	0.0299	1.336
5.2	7.7	110	0.0311	1.475
23.6	7.7	110	0.0344	1.418
60.1	7.7	110	0.0408	1.278
-17.8	14.4	110	0.0297	1.463
-5.2	14.4	110	0.0301	1.294
5.2	14.4	110	0.0335	1.242
23.6	14.4	110	0.0345	1.230
60.1	14.4	110	0.0456	1.042
-17.8	7.7	184	0.0332	1.208
-5.2	7.7	184	0.0318	1.157
5.2	7.7	184	0.0356	1.279
23.6	7.7	184	0.0386	1.314
60.1	7.7	184	0.0479	1.399
-17.8	14.4	184	0.0338	1.122
-5.2	14.4	184	0.0348	1.175
5.2	14.4	184	0.0405	1.378
23.6	14.4	184	0.0431	1.441
60.1	14.4	184	0.0523	1.261
-17.8	17.1	184	0.0343	1.130
-5.2	17.1	184	0.0377	1.281
5.2	17.1	184	0.0414	1.281
23.6	17.1	184	0.0461	1.320
60.1	17.1	184	0.0605	1.173
-17.8	7.7	275	0.0384	3.031
-5.2	7.7	275	0.0352	1.232
5.2	7.7	275	0.0432	1.728
23.6	7.7	275	0.0446	1.447
60.1	7.7	275	0.0484	1.373
-17.8	14.4	275	0.0337	1.169
-5.2	14.4	275	0.0371	1.296
5.2	14.4	275	0.0411	1.129
23.6	14.4	275	0.0464	1.267
60.1	14.4	275	0.0519	1.491
-17.8	17.1	275	0.0369	1.145
-5.2	17.1	275	0.0485	1.244
5.2	17.1	275	0.0429	1.379
23.6	17.1	275	0.0489	1.401
60.1	17.1	275	0.0595	1.338

* Means of 3 replicates

low (17.0% w.b.), normal (21.0% w.b.), and high (24% w.b.) moisture contents as 0.0554, 0.0564, and 0.0704 W m^{-1} °C^{-1}, respectively. Bulk densities were not given. They indicated that the effective thermal conductivity increased linearly with increasing moisture content and increasing bulk density. Samfield and Brock (1958) reported the thermal conductivity of tobacco at moisture content 16.7% w.b. and bulk density of 363.4 kg/m^3 as 0.0926 W m^{-1} °C^{-1}. A relationship between thermal conductivity, initial temperature, moisture content, and bulk density was modeled as:

$$k_p = 0.030827 + 0.000224T + 0.00132\rho_b^{0.5} + 000147M^2 - 002976M \qquad (3)$$

where:

k_p = predicted thermal conductivity (W m^{-1} °C^{-1}),
M = moisture content (% w.b.),
T = initial temperature (°C), and
ρ_b = bulk density (kg/m^3 w.b.).

The model had R^2 value of 0.911 with a standard error of estimate of 0.0025.

Thermal diffusivity of timothy hay

Table 3 shows the thermal diffusivity of timothy hay at various moisture contents, initial temperatures, and bulk densities. The mean thermal diffusivities ranged from 1.042 x 10^{-7} m^2/s at a mean initial temperature of 60.1°C, moisture content of 14.4% w.b., and bulk density of 110 kg/m^3 to 3.031 x 10^{-7} m^2/s at a mean temperature of -17.8°C, moisture content of 7.7% w.b., and bulk density of 275 kg/m^3. The thermal diffusivity showed little or no association between initial hay temperature (r = −0.087), moisture content (r = −0.299), and bulk density (r = 0.221). Ford and Bilanski (1969) determined the thermal diffusivity of single alfalfa stems and reported the thermal diffusivity values as 0.789 x 10^{-7} m^2/s at a temperature of 20°C and moisture content of 46.75% w.b. and 1.076 x 10^{-7} m^2/s at a temperature of 50.0°C and moisture content of 58.54% w.b. Using Dickerson' s method, Jiang et al. (1986) indicated that moisture contents (50, 59, 68, and 80% w.b.) and bulk densities (400, 600, and 800 kg/m^3) had a significant effect on thermal diffusivity of haylage at the 1% level. The thermal diffusivity values ranged from 1.39 x 10^{-7} to 1.55 x 10^{-7} m^2/s. There was no linear relationship between moisture content and thermal diffusivity. Casada and Walton (1989a) measured the thermal diffusivity of burley tobacco bales using a dual thermal probe. Their values ranged from 0.357 x 10^{-7} to 0.922 x 10^{-7} m^2/s. They attributed the variability in the measured values to biological variation within the bale, local variation in density, and the uncertainty in measuring the radial distance to the thermocouple. Kostaropoulos and Saravacos (1997) indicated that the physical structure (porosity and heterogeneity) of foods strongly affected the measured thermal diffusivity values. Local variation in the physical structure of the hay most likely affected the measurement of the diffusivity values. The local air pockets created when making the insertion holes and inserting the dual probes could potentially have caused significant variations in the measurement data.

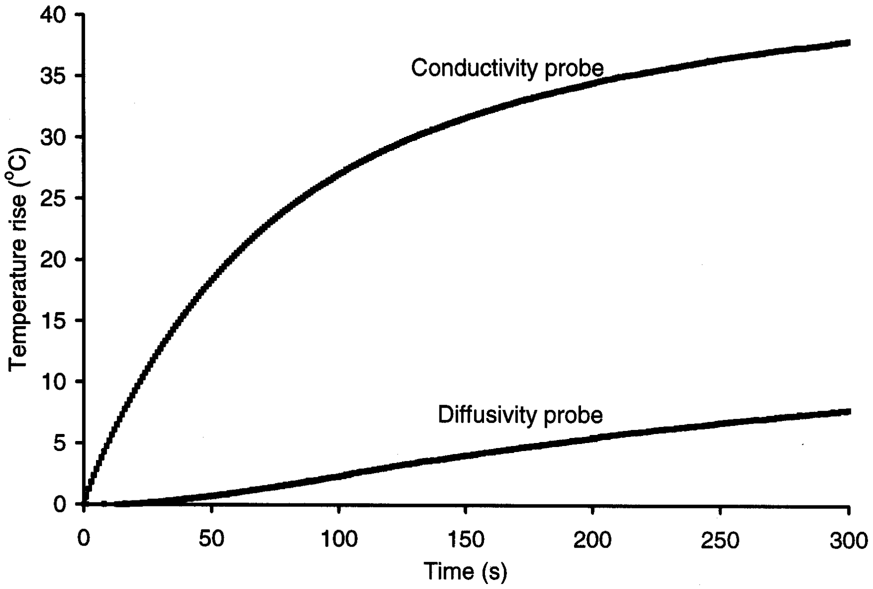

Fig. 2. Typical temperature rise in the timothy hay for conductivity and diffusivity probes at initial hay temperature of -17.8°C, moisture content of 17.7% w.b., and bulk density of 275 kg/m^3.

CONCLUSION

The following conclusions were drawn based upon the experimental study of thermal properties of timothy hay at various temperatures, moisture contents, and bulk densities.

1. The mean thermal conductivity of the timothy hay ranged from 0.0284 to 0.0605 W m^{-1} °C^{-1}. The thermal conductivity values increased with increasing temperature, moisture content, and bulk density. Initial temperature, moisture content, and bulk density had a significant effect on the thermal conductivity values at the 5% significance level.
2. The mean thermal diffusivity of the timothy hay ranged from 1.042 x 10^{-7} to 3.031 x 10^{-7} m^2/s. The thermal diffusivity of the timothy hay showed a nonlinear relationship between temperature, moisture content, and bulk density.

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