Thermal Conductivity of Baled Burley Tobacco

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ABSTRACT

The effective thermal conductivity of baled burley tobacco was determined with a thermal conductivity probe as a function of the major parameters expected to influence the conductivity. The mean value of effective thermal conductivity of baled burley tobacco was higher parallel to the leaf (0.0762 W/m°C) than it was perpendicular to the leaf (0.0453 W/m°C) because the heat was conducted through continuous solid leaf material in the parallel direction while it had to pass through successive air spaces in the perpendicular direction. The effective thermal conductivity increased linearly with increasing moisture content and increasing bulk density. The effective thermal conductivity was highest at the center of the bale and progressively lower toward the edge of the bale.

INTRODUCTION

Burley tobacco growers are currently marketing their tobacco in a relatively new form, the bale, in which roughly 34 kg of cured burley tobacco leaves are packed into a 0.3 m wide, 0.9 m long and 0.6 m high package. The leaves are generally oriented parallel to the 0.3 m x 0.9 m surfaces, the top and bottom of the bale, with the leaf midribs parallel to the 0.9 m dimension. The butts of the midribs are placed at the ends of the bale, while the tips of the leaves overlap in the center of the bale, and the leaves are compressed parallel to the 0.6 m dimension. Any crop year with a surplus of tobacco may result in a number of bales being stored over the summer to be sold during the next marketing season. Presently, few of the physical parameters needed to describe the storage characteristics of the new bales are known. Industrial processors of tobacco will typically dry all of their tobacco, while growers may need to dry the baled tobacco to avoid spoilage if the moisture content is too high. Thus, the loss of moisture from bales during storage or during drying processes is important to both farmers and tobacco processors.

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In a porous absorbing media like the tobacco bale, heat will be evolved during the absorption of the moisture (Henry, 1939). The diffusion of moisture in the bale is a problem of simultaneous heat and moisture diffusion. Thus, moisture diffusion in a porous media may occur entirely due to a temperature gradient (Henry, 1939). Ultimately, the temperature history and subsequently the thermal properties of the tobacco bale must be known to fully describe the diffusion of moisture in the bale.

The determination of thermal properties in the bale is complicated by the bale's anisotropism. Heat flowing parallel to the leaf lamina will be conducted through continuous solid leaf material with relatively high thermal conductivity; whereas, heat flowing perpendicular to the leaf lamina will have to pass through successive layers of air space with comparatively low thermal conductivity. These different mechanisms for heat transfer will result in different thermal conductivities in the two directions.

The thermal properties should also be a function of leaf moisture content, bulk density and stalk position of the tobacco (*relative position of leaves on the stalk*). Because the leaves are oriented in the bale, there may be a variation of local density within the bales that will affect the thermal properties. The temperature will also typically affect at least the thermal conductivity of solid materials (Carslaw and Jaeger, 1959). Thus the variation of the bale's thermal properties with the above parameters must be known if heat or moisture transfer is to be predicted in bales.

Duncan et al. (1966) and Childs et al. (1983) have determined the thermal conductivity of burley and flue-cured tobacco lamina, respectively. Sykes and Johnson (1973) determined the thermal conductivity of shredded flue-cured tobacco during freeze drying. Samfield and Brock (1958), Locklair et al. (1957) and Brock and Samfield (1958) presented the effective thermal conductivity, thermal diffusivity and specific heat of several strip (shredded) tobaccos as a function of moisture content. Kobari et al. (1981) measured the effective thermal conductivity of fibrous sheets of processed tobacco using the line heat source method. They found the effective thermal conductivity parallel to the sheets to be significantly higher than that perpendicular to the sheets. The conductivities for both directions were approximately linear functions of moisture content expressed as the ratio of water volume to pore space volume for moisture contents from 10 to 420% db.

The objective of this research was to determine the effective thermal conductivity of densely packed burley tobacco leaves in bales as a function of leaf moisture

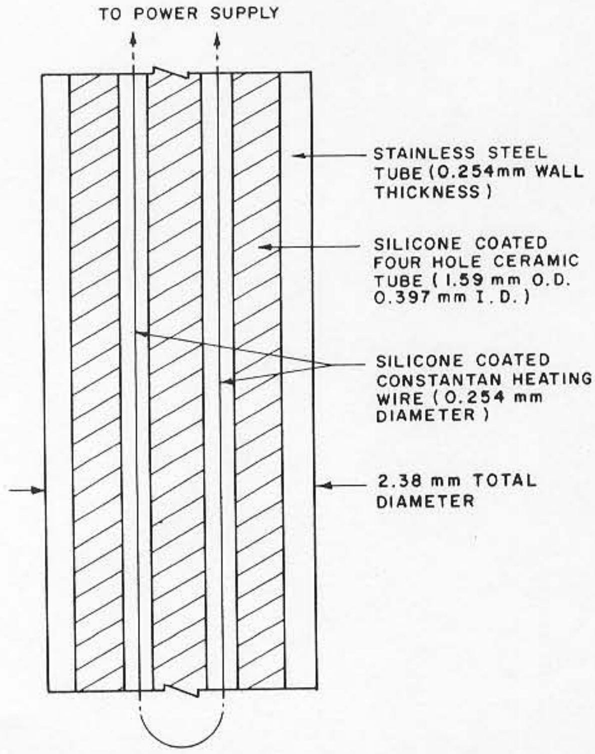

Fig. 1—Schematic of thermal probe.

content, stalk position, bulk density, bale position and direction perpendicular or parallel to the leaf.

METHODS AND MATERIALS

Thermal conductivities of densely packed burley leaves in the bale were determined using two thermal probes of 0.24 cm diameter and 0.29 m length shown in Fig. 1. A 0.254 mm constantan heating wire was coated with a high thermally conductive filled silicone paste before being inserted in the four hole ceramic tube. The ceramic tube was coated in the same manner and was then inserted in the stainless steel tube. The heating wire was connected to a constant voltage power supply that was adjusted to 1.9 V. The voltage was limited to such a low value to reduce moisture diffusion to a negligible level. During a test this voltage was scanned every second with a digital voltmeter and microcomputer. The heating wire loop at the bottom of the probe was protected with a drop of silicone rubber caulk.

Two 0.254-mm diameter iron/constantan thermocouple probes were inserted in the remaining two holes in the ceramic tube. One thermocouple was 3.2 mm above, and the other 3.2 mm below the center of the probe. These thermocouples were scanned every second using the digital voltmeter.

Thermal conductivities were determined using the long time solution of the radial heat diffusion equation at the probe's surface:

$$T = \frac{Q}{4\pi k} \ln(t) \qquad [1]$$

where

T = temperature rise at time (t)
Q = power input per unit probe length, W/m
k = thermal conductivity of the sample, W/m °C.

Regression of temperature rise against ln(t) yielded the slope $Q/4\pi k$ from which the thermal conductivity was calculated.

Variables were direction of heat flow (parallel or perpendicular to the leaf), moisture content (low - 20% db; normal - 26%; and high - 32%), stalk position (bottom, middle and top) and position in the bale. Separate tests were also conducted to determine the effect of temperature and density on thermal conductivity. To determine the effect of temperature, selected bales were tested at additional temperatures, one higher and one lower than the standard temperature at which all bales were tested. To study the effect of density, samples of all except the highest density bales were compressed to one or two levels of density higher than their naturally occurring density.

Natural Density Tests

Tobacco bales were prepared, using recommended baling procedure (Duncan and Smiley, 1982), from burley tobacco at three different moisture levels; low, normal and high moisture, corresponding to approximately 20, 26 and 32% db, respectively. The leaves were stripped from the stalk and collected into three stalk positions (bottom, middle and top) as is typically done on the farm with approximately equal portions of leaves in each stalk position giving a total of nine bales. The low and normal moisture contents were obtained by taking the tobacco out of the curing barn and immediately stripping and baling it at the desired moisture content. The high moisture content was obtained by placing the stripped leaves in racks which were in turn placed in an environmental chamber for conditioning to the desired moisture content prior to being baled. All tests were conducted in an environmental chamber to control temperature and relative humidity which maintained a constant bale temperature and prevented drying.

For each test, a hole was punched in the bale with a 2.38 mm solid rod, and then the probe was inserted in the hole until the top of the probe was flush with the surface of the bale. The thermal conductivity parallel to the lamina was measured by inserting the probe in the top of the bale at six places corresponding to the one-sixth points, one-third points, and twice near the center point of the 0.9 m dimension as shown in Fig. 2. Six corresponding thermal conductivies perpendicular to the lamina were determined indirectly by inserting the probe into the side of the bale as shown in Fig. 2.

When the probe was inserted in the side of the bale, it responded to a combination of the two directional conductivities. Therefore, determining the perpendicular conductivities required a relationship between the two directional conductivities and the measured combination.

In a two dimensional anisotropic system (coordinate axes oriented with the principle axes of conductivity) the measured thermal conductivity, k_x, in any direction is (Carslaw and Jaeger, 1959, p. 48):

$$k_m = \frac{k_x\, k_y}{k_y l^2 + k_x\, m^{2\prime}} \qquad [2]$$

where (1, m) are the direction cosines relative to the

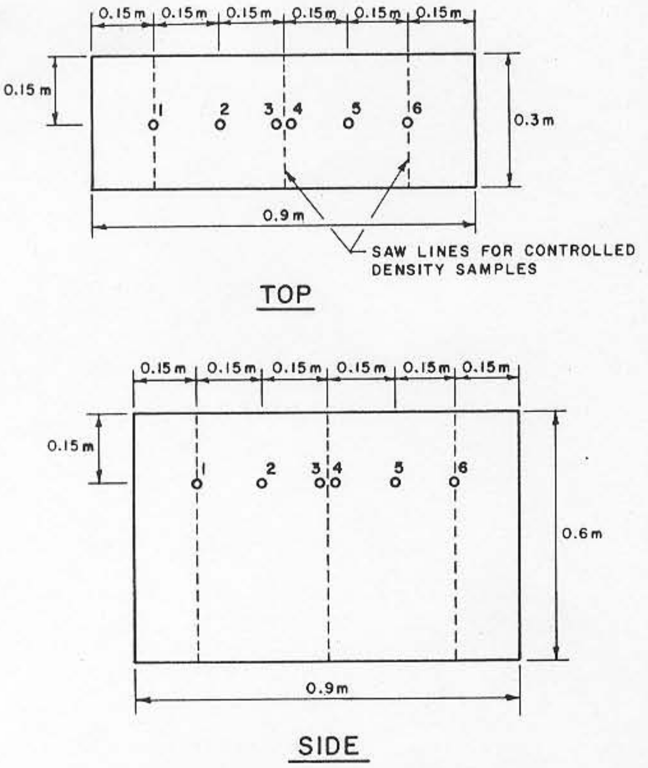

Fig. 2—Bale measurement points.

principal axes of conductivity for the heat flux vector, and k_x and k_y are the principal thermal conductivities.

The apparent thermal conductivity seen by a point (or line) heat source radiating in the x-y plane may be obtained by integrating k_m over one quadrant (because of the symmetry):

$$k_{radial} = \frac{2}{r} \int_0^{\pi/2} \frac{k_x k_y}{k_y \cos^2 \Phi + k_x \sin^2 \Phi} d\Phi \quad \ldots\ldots [3]$$

Integrating gives

$$k_r = \frac{2}{\pi} \sqrt{k_x k_y} \left[\tan^{-1} \left(\frac{k_x}{k_y} \tan \theta\right)\right]_0^{\pi/2} \quad \ldots\ldots\ldots [4]$$

Which is, upon substituting the limits of integration

$$k_r = \sqrt{k_x k_y} \quad \ldots\ldots\ldots\ldots\ldots\ldots [5]$$

Thus, with the parallel direction conductivity known, the combination conductivity from the measurement in the side of the bale could be used to calculate the perpendicular direction conductivity from:

$$k_{per} = \frac{k_{comb}^2}{k_{par}} \quad \ldots\ldots\ldots\ldots\ldots\ldots [6]$$

where

k_{per} = thermal conductivity perpendicular to leaves, W/m °C

k_{comb} = combination thermal conductivity determined by probe in side of bale.

k_{par} = thermal conductivity parallel to leaves as determined by probe in top of bale.

Equation [6] was recommended by Woodside (1959) and verified by Takegoshi et al. (1982) in comparison to a steady state method.

Each test was initiated by the microcomputer which switched on the probe heater and scanned the thermocouple and heater voltages at one second intervals for the remainder of the test. Each test was run for a total of 300 s, and the probe temperature rise between 80 s and 200 s was used for the least-squares best fit of equation [1]. The thermal conductivity was calculated from:

$$k = \frac{Q}{4\pi A} \quad \ldots\ldots\ldots\ldots\ldots\ldots [7]$$

where

A = the slope from the least-squares best fit

Q = the power calculated from the measured heater voltage.

Equation [7] gave the parallel conductivities directly, while the perpendicular conductivities were calculated using equation [6]

Analysis of variance was used to determine the effect of moisture content, stalk position, direction of heat flow, (parallel or perpendicular to leaf) and position in the bale on the thermal conductivity of densely packed burley tobacco leaves. There were two replications. Differences among means were determined by Duncan's new multiple range test. Regression equations were determined by least-squares best fit.

Controlled Density Tests

The thermal conductivities at controlled densities were determined in two samples from each bale. The two samples were extracted from each bale by cutting 0.15 m of length from each end of the bale and cutting the bale vertically in half. The two samples, thus obtained from each bale, were 0.3 x 0.3 m in cross-section and 0.6 m high. These specimen were measured and weighed with a balance to determine their apparent density.

For the controlled density test, the samples were taken from the bales and placed in a compression apparatus which consisted of two reinforced sheet metal plates connected with four 1.3-cm diameter threaded rods with nuts on the ends, which allowed the plates to be compressed to the distance that gave the required sample density. The top plate contained a hole through which the probe could be inserted.

The top of the compression apparatus was placed on the sample and the probe was inserted through the hole in the top plate about 2 cm from the center of the specimen cross-section. A second probe was inserted in the side of the sample for the thermal conductivity measurement perpendicular to the leaf, about 2 cm on the opposite side of the actual point from the first probe.

After tests were carried out with both probes, the sample was compressed to the next higher density level, retested, and then compressed again if necessary. All moisture contents were determined by air oven drying of samples according to ASAE Standard 487.

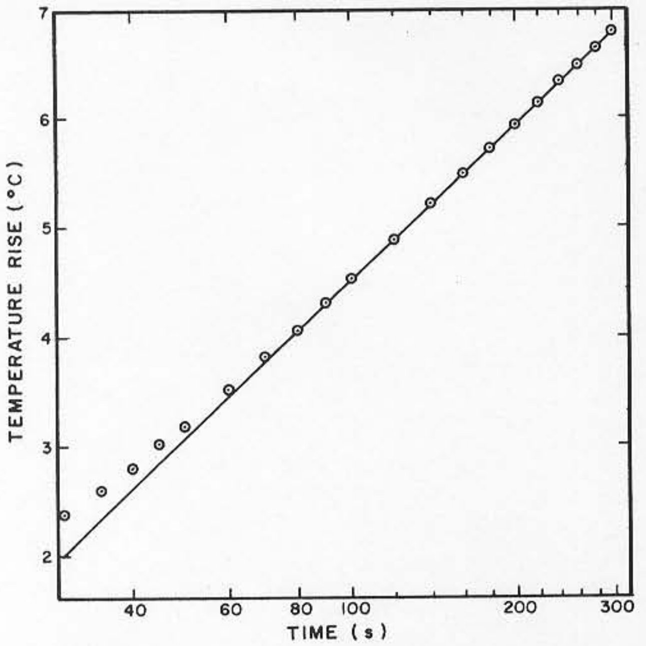

Fig. 3—Temperature rise of a thermal probe in baled burley tobacco as a function of time.

TABLE 1. Mean Values of Effective Thermal Conductivity as a Function of Direction Parallel or Perpendicular to the Leaf, Leaf Moisture Content, Stalk Position and Bale Position

Treatment	Thermal Conductivity $\frac{W}{m^\circ C}$
Parallel to leaves	0.0762 a
Perpendicular to leaves	0.0453 b
High moisture*	0.0704 a
Normal moisture	0.0564 b
Low moisture	0.0554 b
Top stalk position	0.0639 a
Middle stalk position	0.0635 a
Bottom stalk position	0.0549 b
Center of bale	0.0706 a
One-third point of bale	0.0652 b
One-sixth point of bale	0.0466 c

Any means having different letters beside them are significantly different by Duncan's new multiple range test (5% level).

*Moisture levels were approximately 32, 26, and 20% db for high, normal and low moisture, respectively.

RESULTS AND DISCUSSION

Natural Density Thermal Conductivity Tests

The result of a typical test is shown in a semi-log plot in Fig. 3. In the test shown, the probe temperature rise data became linear by 80 s after the beginning of the test, and were still linear at 300 s when the test was concluded. For all tests, the linear portion began between 50 and 80 s after the test was initiated and ended after at least 200 s; thus, the data between 80 and 200 s were used for determing the thermal conductivity. The R^2 value for this test was 0.9998, while the R^2 values for all tests were at least 0.9994. The high R^2 values show that the mathematical model (equation [1]) predicted temperature rise without need for a time correction factor.

The analysis of variance showed that the effect of direction parallel or perpendicular to the leaf, leaf moisture content, stalk position and bale position on thermal conductivity was significant at the 0.01 level. The direction x moisture content, direction x bale position, moisture content x bale position, stalk position x bale position and direction x stalk position x bale position interactions were significant at the 0.01 level. The moisture content x stalk position and direction x moisture content x stalk position x bale position interactions were significant at the 0.05 level.

Mean values of the thermal conductivity are shown in Table 1 as a function of direction parallel and perpendicular to leaf, leaf moisture content, stalk position and bale position. The mean for the low moisture content was, unexpectedly, not different from the mean for normal moisture content. The interaction between direction, bale position and moisture content shown in Table 2 indicates that the difference between low and normal moisture contents was not significant due to the perpendicular direction having a slightly higher mean at low moisture content than at normal moisture content for several stalk position-bale position combinations. The overall data in Table 2 show that the middle and top stalk positions (perpendicular direction)

TABLE 2. Overall Effective Thermal Conductivity Data

Moisture Content (% db)	Stalk Position	Effective Thermal Conductivity (W/m °C) Center: Parallel	Center: Perpendicular	One-Third Point: Parallel	One-Third Point: Perpendicular	One-Sixth Point: Parallel	One-Sixth Point: Perpendicular
18.7	Bottom	.0741	.0448	.0666	.0358	.0462	.0318
21.8	Middle	.0921	.0547	.0748	.0474	.0545	.0377
21.7	Top	.0723	.0471	.0706	.0573	.0545	.0346
22.4	Bottom	.0763	.0521	.0677	.0440	.0511	.0254
26.4	Middle	.0980	.0493	.0737	.0427	.0426	.0298
28.5	Top	.0864	.0398	.0877	.0521	.0623	.0350
28.8	Bottom	.0928	.0457	.0903	.0483	.0611	.0344
37.5	Middle	.1154	.0796	.0974	.0485	.0625	.0427
36.4	Top	.0966	.0526	.0993	.0699	.0877	.0426

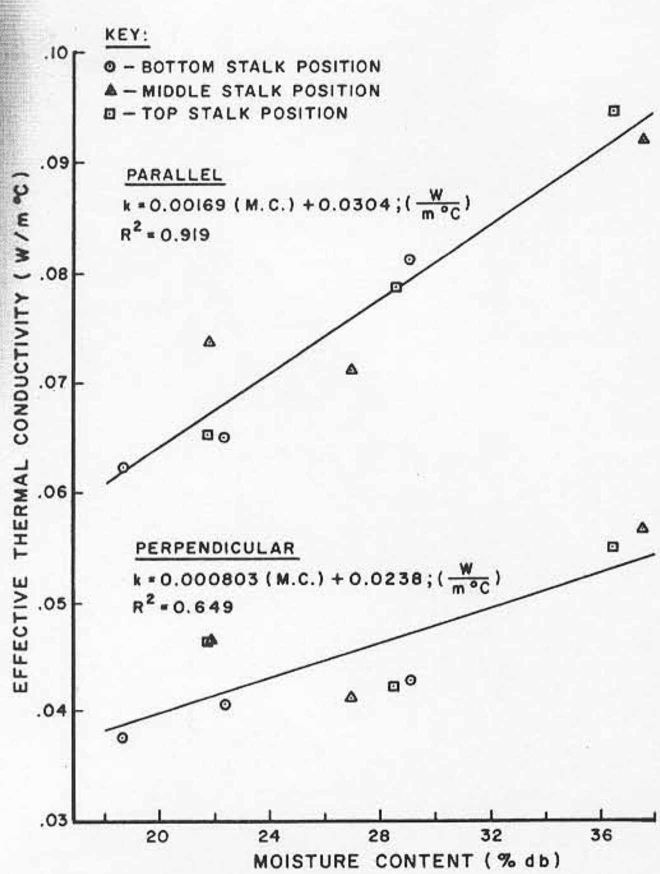

Fig. 4—Effective thermal conductivity as a function of moisture content at natural densities.

generally had higher thermal conductivities at low moisture, as compared to normal moisture, in each case.

Table 1 shows the variation of thermal conductivity with position in the bale. Because the bales were made in the usual manner with the leaves oriented with the stems toward each end of the bale, and the tips overlapping in the center, the ends of the bale were less dense than the rest of the bale. This lower density resulted in more air space and less solid material at the edges of the bale and resulted in a lower effective thermal conductivity. The very center point of the bale had an even higher thermal conductivity than the one-third point. This was because the overlapping of the leaves at the center of the bale caused this center to have a higher density than the one-third point of the bale.

Figure 4 shows the average effective thermal conductivity in the bale as a function of actual moisture content for each bale. Each point on the graph is the average of six measurements in the given bale. The regression lines in Fig. 4 for the parallel and perpendicular directions had R^2 of 0.919 and 0.649, respectively. The least-squares best fit line for effective thermal conductivity parallel to the leaf lamina had a greater slope than that perpendicular to the lamina. This was due to the different mechanisms for heat transfer in the two directions. In the parallel direction, most of the heat transfer took place by conduction through the continuous solid leaf material. Thus, the effective thermal conductivity parallel to the leaf was nearly as strong a function of moisture content as was the thermal conductivity of the solid leaf. The total heat transfer

TABLE 3. Constants from Linear Regression of Effective Thermal Conductivity as a Function of Moisture Content for Each Bale Position

Bale Position	Direction	Slope (W/m°C)/% M.C.)	Intercept (W/m°C)	R^2
Center	Parallel	001726	.0427	0.682
	Perpendicular	.000964	.0258	0.314
1/3-Point	Parallel	.002070	.0234	0.810
	Perpendicular	.000841	.0268	0.326
1/6-Point	Parallel	.001462	.0185	0.539
	Perpendicular	.000604	.0185	0.508
Average	Parallel	.001689	.0304	0.919
	Perpendicular	.000803	.0238	0.649

(and, thus, the effective thermal conductivity) perpendicular to the leaf was strongly affected by the air spaces and therefore was not as strongly affected by moisture content as was that in the parallel direction.

Since the data in Fig. 4 are for the bales at their naturally occurring densities, the apparent effect of moisture content also included the effect of the bales' bulk density. The overall bulk density of the bales depended on the moisture content of the tobacco being baled. These densities naturally resulted from the higher moisture content tobacco compressing more during baling than the lower moisture content tobacco. Ultimately, in a typical bale when the moisture content is known, the relationship presented in Fig. 4 can be used to predict the average effective thermal conductivity since it accounts for the effect of moisture content and of natural density on the conductivity. The data in Table 3 can be used to predict conductivities in the same manner if bale position is to be taken into account.

Figure 5 shows the effective thermal conductivity in the parallel and perpendicular directions as a function of bulk density in individual samples, i.e. at constant moisture content. This limited data obtained for individual samples with varying densities indicated a linear dependence of thermal conductivity on density. The linear relationship would be expected since it is reasonable that the amount of heat conducted would increase directly with any increase in the amount of solid material present for conduction.

Variable Temperature Conductivity Tests

The bale measurements that were repeated for different temperatures showed that there was only a slight increase in effective thermal conductivity with increasing temperature in the tested temperature range: 13 to 35°C. The variation of effective thermal conductivity with temperature is linear and, thus, the average thermal conductivity for a given temperature range may be properly used. Such a linear relationship is typical for a limited temperature range (Carslaw and Jaeger, 1959).

The very small change in effective thermal conductivity as a function of temperature indicated that there is little need to consider the effect of temperature, especially beyond assuming that the values obtained at 21°C (70°F) are correct averages for useful temperature ranges. The effects of moisture content and density (bale position) are much greater than the temperature effect

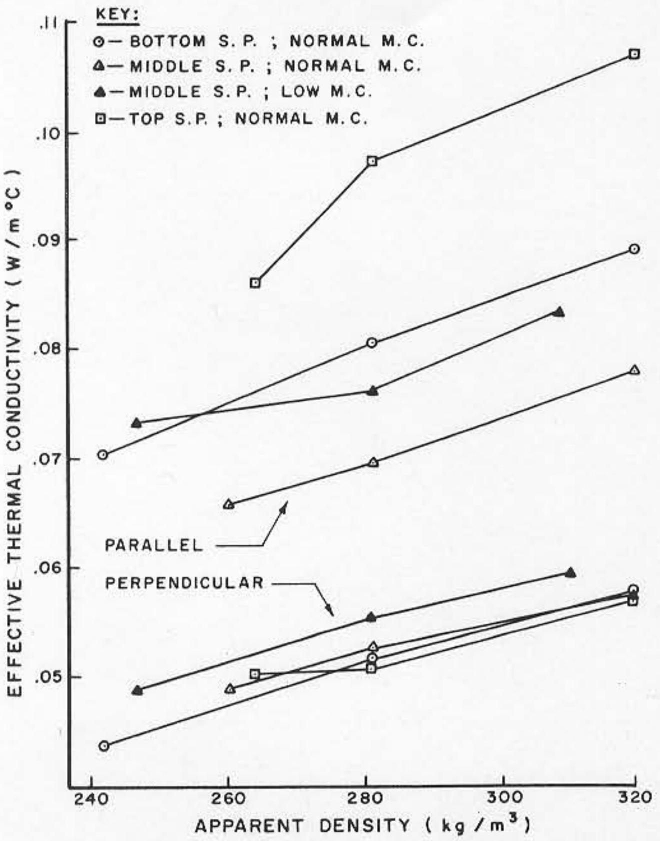

Fig. 5—Effective thermal conductivity as a function of apparent density for individual samples (i.e. at constant moisture content).

over typical ranges of the parameters. Moreover, the variation from random variation seen in the data shows that considering the small effect of temperature on effective thermal conductivity in the bale would be superfluous.

CONCLUSIONS

The following conclusions were developed based on the results of this study of the thermal conductivity of burley tobacco bales:

1. The effective thermal conductivity was significantly higher parallel to the leaf than it was perpendicular to the leaf because the heat was conducted through continuous solid leaf material in the parallel direction, while it had to pass through successive air spaces in the perpendicular direction.
2. The effective thermal conductivity increased linearly with increasing bulk density for both directions over the tested range; but, the rate of increase was higher for the parallel direction because of the different mechanisms for the heat transfer in the two directions.
3. The effective thermal conductivity increased linearly with increasing moisture content for both directions in the range of 18 to 38% dry basis moisture content with a higher rate of increase in the parallel direction because of the differences in the mechanisms for the two directions. This moisture effect was exaggerated in naturally occurring bales since the bale bulk density, with its effect on conductivity, also increased with moisture content.
4. The effective thermal conductivity was highest at the center of the bale and progressively lower toward the edges of the bale because the bale's oriented leaves caused the bale bulk density to be higher at the center and lower toward the edges of the bale.
5. The effective thermal conductivity was lower for bales from the bottom stalk position than for those from the top and middle stalk positions because the bottom stalk position leaves normally have a lower moisture content than the other two positions.
6. The effective thermal conductivity increased linearly with temperature from 13 to 35°C but the increase was negligible compared to the random variation or compared to the changes caused by the other significant parameters.

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