EFFECT OF MOISTURE ON THERMAL CONDUCTIVITY OF FIBROUS BIOLOGICAL INSULATING MATERIALS

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ABSTRACT

In recent years, there has been increased interest in the use of biological insulating materials, as is evident by the growing number of publications appearing in the literature. In the tropics, naturally occurring biological materials such as bagasse and coconut fibers have found use both in low-temperature insulation applications and in compressed board form; these have been used for dropped ceilings and partitions. There is, however, insufficient information available on the thermophysical properties of these fibrous materials.

To get data on thermophysical properties of local biological fibrous insulating materials, a hot-plate/cold-plate apparatus was designed and fabricated. The reliability of this experimental setup was ascertained using Standard Reference Material (SRM) 1451 provided by the National Institute of Standards and Technology (NIST) of the United States.

This paper presents the design of the rig and results of thermal conductivity measurements for bagasse fibers over the density range of 45 kg/m^3 to 110 kg/m^3. Test data showed the characteristic hook-shaped graph of thermal conductivity vs. density for fibrous insulating materials, and the minimum value of thermal conductivity occurred at 67 kg/m^3. When 5% moisture by weight was applied in atomized form, the thermal conductivity of bagasse increased by about 17% over the test density range.

INTRODUCTION

Financial constraints and the world energy crisis have fostered a more aggressive search for new thermal insulating materials and more in-depth research, understanding, and prediction of thermal insulating properties. Apart from the energy bill, thermal insulating properties of construction materials have a direct impact on the comfort of building occupants.

In the tropics, naturally occurring biological fibrous materials such as bagasse and coconut fiber have proven to be cheap, readily available, and effective low-temperature insulators. In slablike form, these materials are being used for dropped ceiling and partitions. The limited use of these materials in the thermal insulating field is a direct result of insufficient information on their thermophysical properties.

Actual thermal conductivity measurements have always been a delicate and somewhat complex procedure. This is more so for fibrous materials, which consist of a bed made up of solid fibers and a gas, usually air, with either two bounding surfaces or a bounding surface and a free surface.

Over the years, steady-state thermal conductivity measurements have been accepted to provide the most accurate and reliable results. The reliability of thermal conductivity results depends to a great extent on the specimens under test. The test specimen must be a true representation of the material in the actual usable form. This condition is critical when dealing with building materials, which are usually composites. One way of overcoming this problem is by using large test specimens.

To determine the thermal conductivity of large, 90-cm by 90-cm slablike specimens (both fibrous and solid), a low-cost, water-activated hot-plate/cold-plate steady-state thermal conductivity apparatus was designed, fabricated, tested, and calibrated. Due to the size and large monitoring surface, test specimens that are truly representative of the actual materials were easily tested. The simplicity of the design and operation procedure, together with the large specimen size and reliable experimental data, makes this apparatus appropriate for thermal conductivity measurements of a wide range of slablike materials under steady-state conditions.

The design was geared toward satisfying the following conditions:

- to construct an apparatus that would use specimens large enough to give a true representation of the material under normal use;

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- to make the operation of the apparatus simple so that setting up, taking measurements, and changing specimens would be easily and quickly carried out; and
- to eliminate the inherent problems associated with conventional steady-state methods of thermal conductivity measurements (guarded hot plates).

From an in-depth study of the thermal conductivity methods and measuring devices (Ozil 1976; BSI 1973, 1986; Griffiths 1942; Pratt and Ball 1956; Ball 1968; ASTM 1971, 1976a, 1976b; Mumaw 1974; Brendeng and Frivik 1974; Zabawsky 1968; Goldratt and Greenfield 1978; Corsan 1984; Onyejekwe and Onyegegbu 1983) of existing equipment, an apparatus using two 900-mm by 900-mm water-activated plates was proposed. The principle of operation employed the steady-state method.

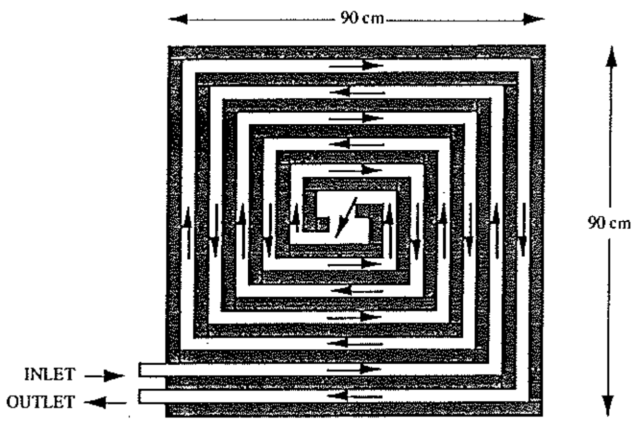


Figure 1 *Spiral alternate flow channel arrangement for cold plate/hot plate.*

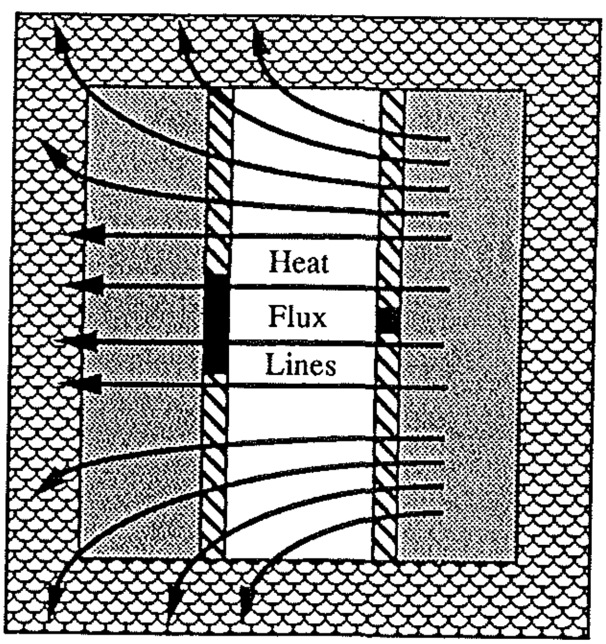


Figure 2 *Heat flux lines across specimen—model.*

The main components of the apparatus were the hot and cold constant-temperature plates. Both plates employed an alternate-flow spiral channel arrangement, as shown in Figure 1. This flow arrangement provided a uniform temperature over the contact face of the plates, thereby constant-temperature cold and hot plates were obtained (BSI 1973) and, therefore, ensuring a constant and uniform temperature difference between these two plates. The heat transfer across any slablike specimen subjected to these conditions over a sufficiently long period will acquire steady-state conditions.

On the cold-plate surface, the central area was continuously monitored by a heat flow probe measuring 120 mm by 100 mm. This left at least 390 mm around the metered area to compensate for lateral heat flow and edge losses; it also acted as the guard area. With such a large guard area, one-dimensional heat flow over the metered area was ensured (Figure 2).

FABRICATION

For a constant-temperature plate to be most effective, it should be fabricated from a good heat-conducting material. Considering thermal conductivity, density, availability, and cost, aluminum was selected as the most appropriate material for the plate fabrication. Due to the size, the best method for fabricating the plates was to sand cast the face plate together with the ridges. To form the hollow spiral water flow channels, a 6-mm-thick aluminum plate with a 2-mm-thick rubber gasket was secured onto the ridges on the back of the plates by screws. The contact face of both plates was machined to provide a smooth, level surface to ensure good thermal contact between the plates and specimens.

The plate temperatures were monitored using chromel-alumel thermocouples. This type of temperature sensor was considered most appropriate due to its size, accuracy of measurement, quick response time, and low cost. Thermocouples were embedded into the inner side of the contact face and completely sealed, preventing erosion effects on the bulbs due to the continuous flow of water. These thermocouples were used to check the effectiveness of the design as a constant-temperature plate.

The thermocouple points were arranged in a systematic manner over the inner surface of the plate, as shown in Figure 3. A single set of readings from any one plate gave the temperature variation from the center of side AB to the middle of the plate and along the circumference of the circle of radius 294 mm about the center of the plate. By comparing the temperature along the two known areas, the temperature gradient from the middle of the plate to the ends was known and, due to the alternate-flow spiral channel design, the plates were uniformly heated radially about the center, then the temperature variation along any other axis would be the same. This was verified by comparing temperatures at

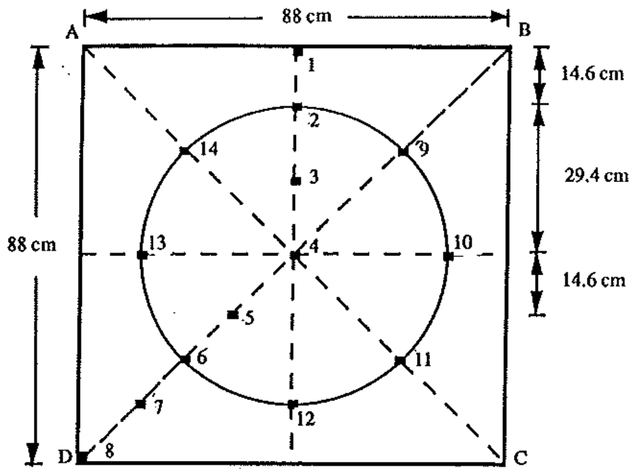


Figure 3 Thermocouple arrangement on cold plate/hot plate.

points 9 and 14 along the circumference with the corresponding points 2 and 6 along the diagonals, which all showed the same temperature.

TEST RIG SETUP

As shown in Figure 4, both plates were insulated with 50-mm-thick polystyrene (thermal conductivity value of 0.036 W/m·K [Baumeister and Avallone 1985]) on the outer surface and, on the contact surface, 6-mm-thick neoprene rubber (thermal conductivity value of 0.20 W/m·K [Perry et al. 1987]) was used to compensate for irregularities on the specimen surface and to provide good thermal contact between the specimens and the constant-temperature plates. Wooden frames were used to hold the plates in a vertical position to facilitate easy change of specimens.

In the closed arrangement (test mode) of the rig, four bolts attached to the wooden frames were used to pull the plates together to ensure good thermal contact between the constant-temperature plates and the specimens via the neoprene rubber. The 52-mm-thick rigid specimen holder ensured the specimen's thickness of 52 mm.

Figure 5 shows a schematic of the hot-plate system. Constant-temperature hot water was circulated from a 200-L insulated constant-temperature storage tank through the hot plate by a circulating pump.

Figure 6 shows a schematic of the cold-plate system. Constant-temperature cold water was circulated from the reservoir of a cooling tower through the cold plate via a circulating pump. Heat flow meters, pressure gauges, and thermometers were set in both systems for monitoring as shown.

On each plate, an external monitoring system was used to provide necessary data without disturbing the operation. The surface temperature of the plates was continuously monitored. The heat flow across the specimen was measured by the heat flow meter via a transistorized 6-mm-thick probe (a thermopile). The probe was placed at the center of the cold plate in direct contact with the cold face of the specimen. This probe (of area 120 mm by 100 mm) measured the one-dimensional heat flux through the specimen over this area. These data were relayed to the heat flowmeter via the thin wire leads. This probe also had a built-in temperature sensor that monitored the cold face temperature. The hot face temperature was monitored by a flat resistor that was connected directly to the data-acquisition unit. All the

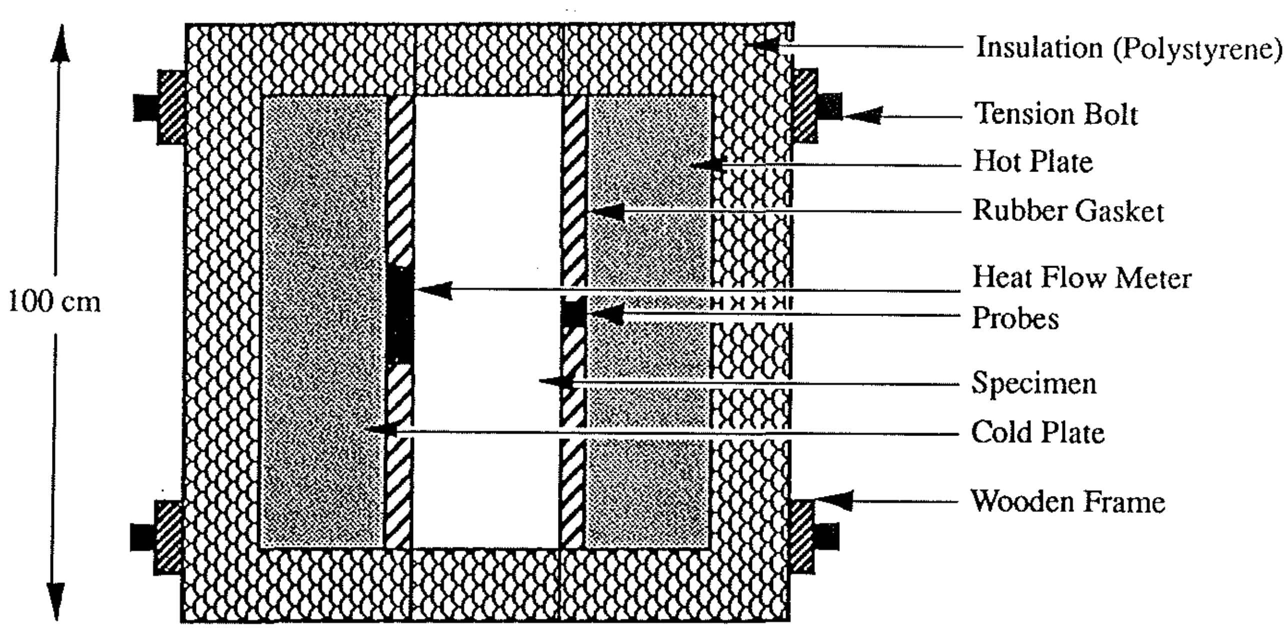


Figure 4 Cross section of thermal conductivity rig (closed arrangement).

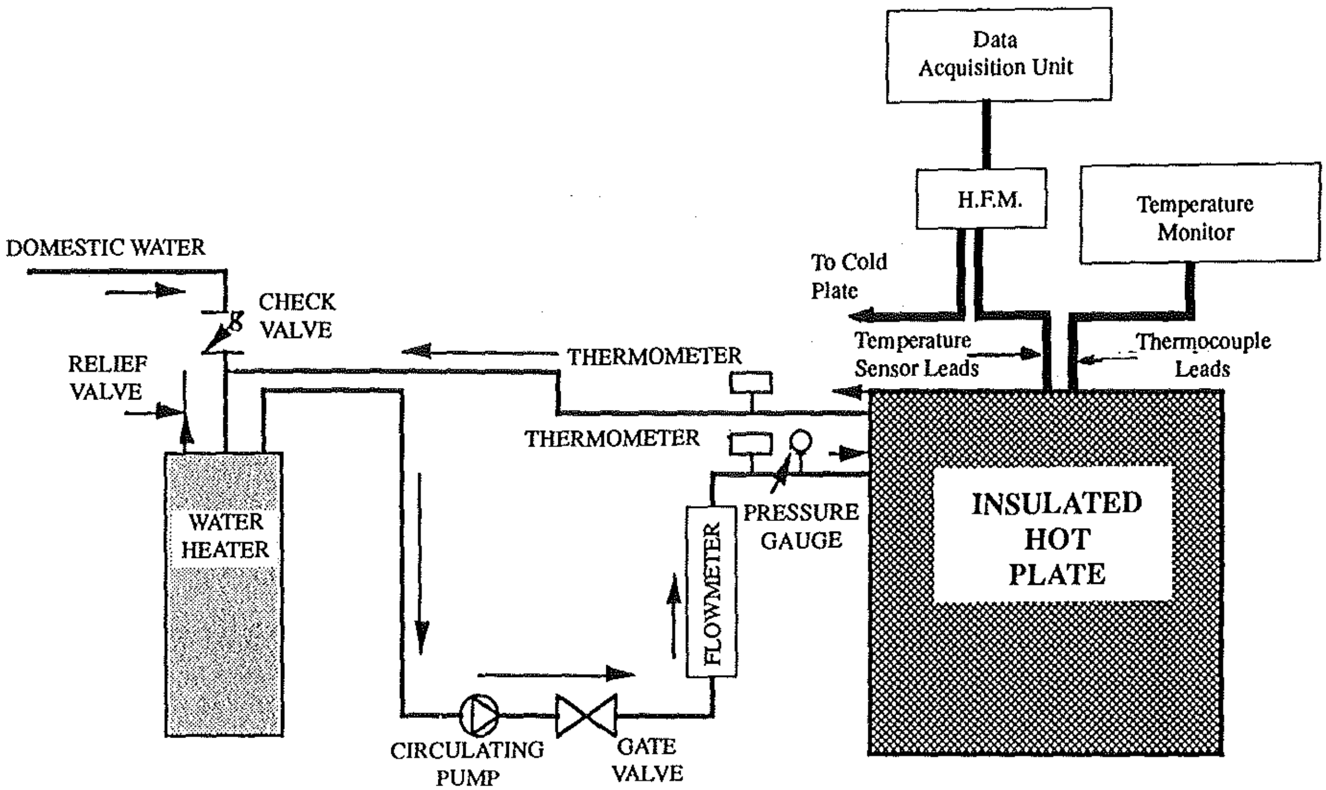


Figure 5 *Hot plate schematic showing water flow direction and equipment arrangement.*

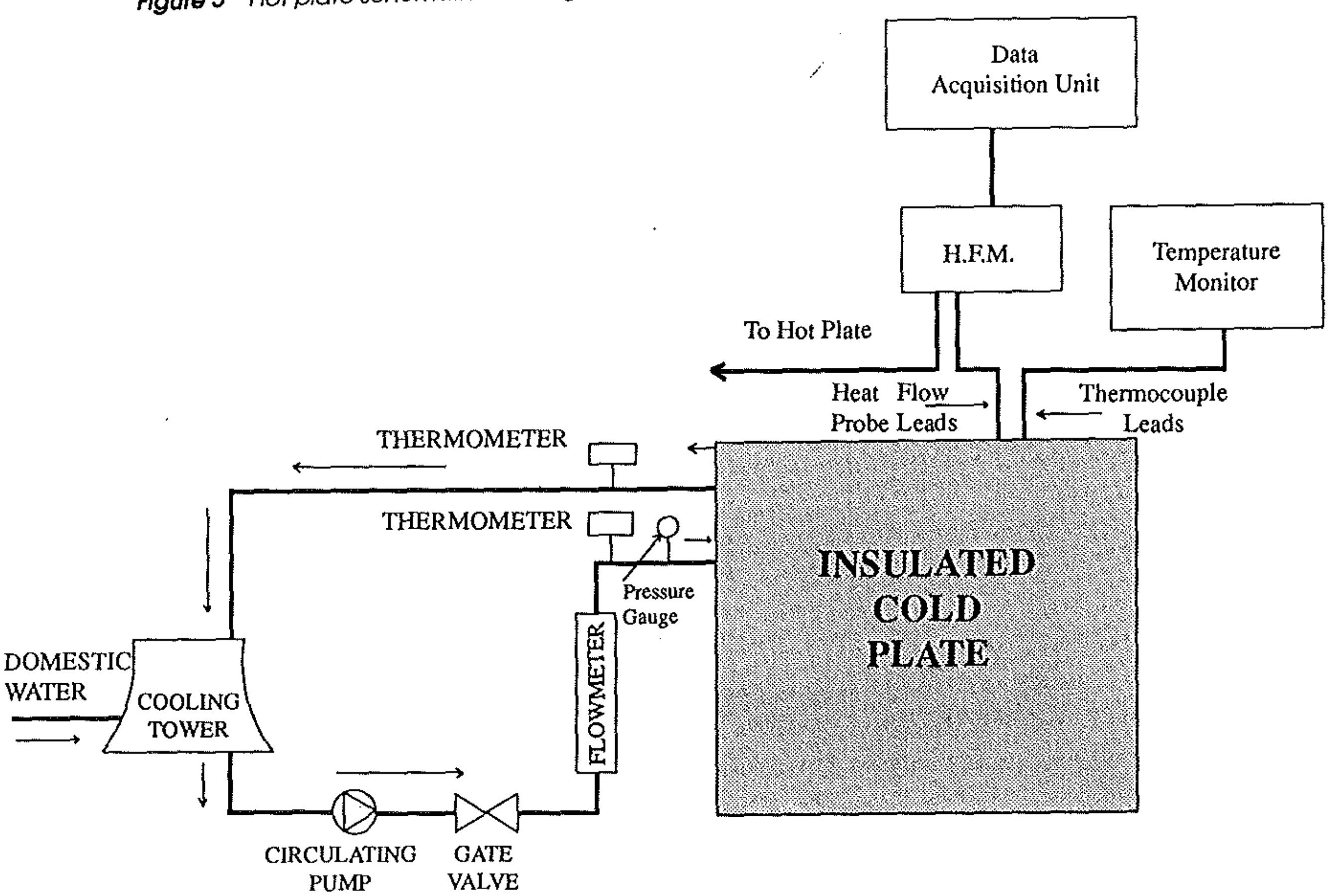


Figure 6 *Cold plate schematic showing water flow direction and equipment arrangement.*

information was relayed to a microprocessor-controlled data-acquisition unit that stored the information at 20-second intervals. This unit used the data to calculate and store the instantaneous value of conductance and the average values of heat flux, conductance, and hot face and cold face temperatures. Printed copies of the data were accessible at pre-set intervals of 20 seconds, 10 minutes, 30 minutes, 60 minutes, or as required. The heat flow meter was precalibrated by the manufacturer (JII 1985). The precision of the displayed instantaneous thermal conductivity values was ±3%. The average value was a statistical average of instantaneous readings at 20-second intervals, i.e., the average value after one hour is the average of 108 readings and after four hours is the average of 720 readings. These statistical data were calculated and printed by the data-acquisition unit.

CALIBRATION

Constant-Temperature Plates

According to BSI (1973), the necessary conditions of operation for any constant-temperature thermal conductivity measuring device requires the plate to have a maximum spread of 1°C between the highest and lowest readings in any set of readings on any individual hot or cold plate over the plate surface between any two points, and the average temperatures calculated for both the hot and cold faces shall be valid only when at least three consecutive conductivity values have a maximum spread of 2%.

The temperature readings from the thermocouples were continuously monitored by a multichannel temperature monitor and checked at half-hour intervals for both the cold plate and the hot plate. The temperature variation over the plate surfaces showed a maximum spread of 0.6°C between the highest and lowest readings on any individual set of readings over the hot or cold plate.

These results (in Tables 2, 3, and 4) show that the constant-temperature plates operated well within the limits set by BSI (1973), thereby confirming the accuracy, reliability, and validity of the design as an effective constant-temperature plate. ASTM C518 (ASTM 1976b) requires control of the warm and cold plates so that the temperature during the test period shall not fluctuate by more than 0.5% of the temperature difference between the hot and cold plates. In addition, the surface temperature fluctuations on the face of the meter contiguous with the specimen must be less than 0.5% of the temperature drop across the specimen.

From Tables 2, 3, and 4, the temperature fluctuations on the cold plate over the metered area are 0.1°C, 0.2°C, and 0.1°C, respectively, and 0°C on the hot plate for the last three successive readings. The average temperature gradient across the specimen was 13.3°C. This shows that the hot plate operates within ASTM standards, whereas the cold plate shows a 0.7%, 1.5%, and 0.7% difference compared to ASTM requirements of 0.5% difference.

Test Rig

According to the National Institute of Standards and Technology (NIST), to determine the accuracy of an apparatus of this type, tests on a standard reference material (SRM) of known thermal conductivity must be carried out. The SRM should meet the following criteria (ASTM 1978; Bertasi et al. 1978).

1. The material should be mechanically and chemically stable through the intended test temperature range and possess long-term stability under ambient conditions. Ideally, the material should be unaffected by heat treatment or at least be in a stabilized condition after a prescribed heat treatment.
2. The material should be capable of being manufactured in sufficiently large and homogeneous lots to permit a practical number of test specimens per calibrated section or, alternately, the manufacturing process should yield test specimens of the required reproducibility and homogeneity to be practical.
3. The material should be representative of the thermal transport characteristic of a generic class of commercial insulation material or, alternately, be a class of material that yields useful diagnostic information about the thermal test conditions.

In the United States, the development of standard reference materials (SRM) generally is considered to be within the classical function of NIST (ASTM 1978). To verify the accuracy of the test rig, an SRM supplied by NIST was used. This SRM was Standard Reference Material 1451—Thermal Resistance Fibrous Glass Blanket. This SRM satisfied all the criteria of an SRM and was used in accordance with the NIST specifications. SRM 1451 has the following specifications:

Mass	= 140.52 g
Thickness	= 25.4 mm
Area	= 610 mm × 610 mm
Density	= 14. 9 kg/m^3

The SRM was centrally located in a sample holder of external dimensions of 900 mm by 900 mm and internal dimensions of 610 mm by 610 mm and thickness of 25.4 mm.

The calibration test was conducted at a mean temperature of 30.6°C and in accordance with NIST specifications. The NIST-certified conductance value for SRM 1451 was found by interpolation from the supplied data, as shown in Table 1.

The average experimental test data for three calibration tests on SRM 1451 are given in Tables 2, 3, and 4. For each test, a settling time of 108 hours was allowed before the first readings were recorded.

From the experimental test data of Tables 2, 3, and 4, the following average values were obtained.

TABLE 1 **Interpolated Values from NIST Data for SRM 1451**

Values	Temperature (°C)	Density (kg/m^3)	Conductance (W/m^2·°C)
Certified values	27	14	1.631
	37	14	1.724
Interpolated values	30.6	14	1.664
Certified values	27	16	1.560
	37	16	1.647
Interpolated values	30.6	16	1.591
Interpolated values	**30.6**	**14.9**	**1.6275**

TABLE 2 **Experimental Test Data—Average Values***

Time			Average Values			
Hr.	Min.	Sec.	Heat Flux (W/m^2)	Cold Plate Temperature (°C)	Hot Plate Temperature (°C)	Conductance (W/m^2·°C)
0	0	20	21.7	23.9	37.3	1.62
1	0	40	22.0	24.0	37.2	1.66
2	0	40	21.9	24.1	37.2	1.66
3	0	40	22.0	24.0	37.2	1.66
4	0	40	22.0	24.0	37.2	1.66

*Results from Data Acquisition Unit—taken after 108 hours settling time.

TABLE 3 **Experimental Test Data—Average Values***

Time			Average Values			
Hr.	Min.	Sec.	Heat Flux (W/m^2)	Cold Plate Temperature (°C)	Hot Plate Temperature (°C)	Conductance (W/m^2·°C)
0	0	20	21.6	23.8	37.4	1.58
1	0	40	21.9	23.9	37.3	1.64
2	0	40	22.0	23.9	37.2	1.65
3	0	40	21.9	24.0	37.2	1.65
4	0	40	21.8	24.1	37.2	1.66

*Results from Data Acquisition Unit—taken after 108 hours settling time.

TABLE 4 **Experimental Test Data—Average Values***

Time			Average Values			
Hr.	Min.	Sec.	Heat Flux (W/m^2)	Cold Plate Temperature (°C)	Hot Plate Temperature (°C)	Conductance (W/m^2·°C)
0	0	20	21.4	24.0	37.4	1.60
1	0	40	21.9	23.9	37.3	1.63
2	0	40	21.9	24.0	37.2	1.65
3	0	40	22.0	23.9	37.2	1.65
4	0	40	21.9	23.9	37.2	1.65

*Results from Data Acquisition Unit—taken after 108 hours settling time.

Conductance Values:

Certified values (NIST) = 1.6275 W/m^2·°C

Mean steady-state values (experimental) = 1.65 W/m^2·°C

Mean temperature (steady state) = 30.6°C.

These results showed that the percentage difference between the experimental and certified values is

$$\frac{1.65 - 1.6275}{1.6275} \times 100\% = 1.38\%.$$

NIST specified that the thermal conductance values of this SRM material are expected to be within 3% of the computed certified values for the experimental range of −23°C to 57°C.

Hence, the cold-plate/hot-plate apparatus was operating well within the limits set by NIST for this SRM, thereby confirming the accuracy and reliability of the test apparatus as a means of determining the thermal conductivity of flat slablike specimens.

EXPERIMENTAL PROCEDURE

The thermal conductivity measurements were conducted under steady-state conditions in accordance with BSI (1973). To determine steady-state conditions, the necessary parameters were continuously monitored after switching on the test apparatus with the specimen in place. The slablike specimens were allowed as much as 96 hours settling time to achieve steady state. When four consecutive readings, at one-hour intervals, showed a maximum spread of 1% between the highest and lowest conductance values, the specimen was considered to have reached steady state. This was then confirmed by two subsequent measurements at not less than one-hour intervals (BSI 1973). The final steady-state thermal conductance readings were then taken at one-hour intervals. The average thermal conductance readings were valid when at least three consecutive values had a maximum spread of 2%. The thermal conductivity value of the specimens was then calculated from the conductance values (BSI 1973).

EXPERIMENTS

Thermal conductivity measurements were carried out on 52-mm-thick bagasse specimens (in a 52-mm-thick specimen holder) over the density range of 45 kg/m^3 to 110 kg/m^3 for air-dried bagasse (9% moisture by weight above bone-dry conditions) and 5% moisture by weight above the air dry conditions. A specimen holder measuring 660 mm by 660 mm by 52 mm with aluminum foil covering on both sides was used to hold the loose bagasse in a slablike form. The lowest possible density at which the bagasse specimens could exist under normal settling conditions due to gravity was 45 kg/m^3. The density was varied by varying the mass of bagasse in the specimen holder. The moisture was applied uniformly in atomized form throughout the specimen. The 5% moisture by weight was spray-applied to the loose, weighed specimen while being continuously stirred to ensure uniformity of application. The moist specimens were then reweighed to check the percentage moisture and immediately packed and sealed into the specimen holder. Under testing, the specimens were sealed airtight and, after testing, visual checks were made for moisture migration on the cold surface and the specimen was reweighed to check for moisture loss.

For each experiment conducted over the density range, three specimens were prepared and tested under the conditions outlined here. The average values of these were recorded and are presented as the thermal conductivity values of the specimens in Tables 5 and 6.

TABLE 5 **Experimental Results for Air-Dried Bagasse—Atmospheric Pressure (9% Moisture by Weight)**

Atmospheric Pressure		
Mean test temperature	=	32°C
Mean fiber diameter	=	0.28 mm
Percentage dust	=	2% by weight
Specimen thickness	=	52 mm

Density (kg/m³)	Thermal Conductivity (W/m·K)
47	0.0322
53	0.0296
54	0.0291
61	0.0265
67	0.0255
72	0.0265
77	0.0270
80	0.0276
88	0.0291
99	0.0324
110	0.0348

DISCUSSION OF RESULTS

Test Rig

The test apparatus was designed to determine the thermal conductivity of slablike specimens under steady-state conditions using the fundamental one-dimensional steady-state principles. The simple design proved to be an accurate way of measuring steady-state thermal conductivity and showed the following advantages over conventional designs.

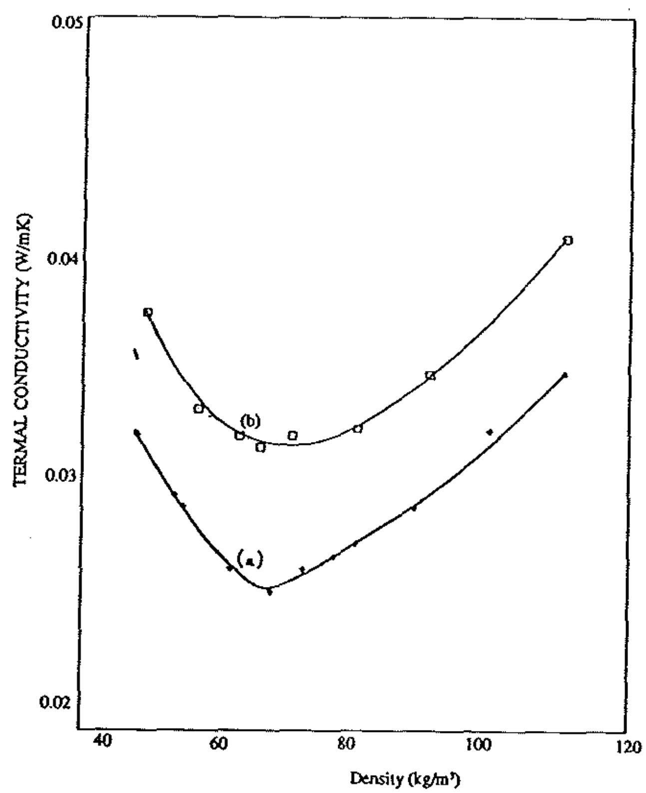
- The size of the apparatus and specimens accounted for lateral heat flow and edge losses, and ensured one-dimensional heat flow at the central monitoring area.
- The size of the specimens allowed for a true representation of the material to be tested.
- The use of water as the temperature-controlling medium allowed for:
  (a) easy variation of hot-plate and cold-plate temperatures and
  (b) elimination of the inherent errors and complications encountered with electrical heating systems.
- Specimens are changed easily and quickly.
- Simple operational and measurement principle.
- The system, once started, operated automatically.

BAGASSE

Figure 7 shows the plot of experimental thermal conductivity vs. density of the experimental results from Tables 5 and 6 for bagasse specimens. These graphs clearly show the characteristic hooked shape for fibrous materials. As can be seen from this figure, the critical density occurs at approximately 67 kg/m^3 for both cases.

The tests on air-dried bagasse and air-dried bagasse with 5% moisture added showed the effect of moisture on the thermal conductivity of the bagasse. As expected, the presence of a small percentage of moisture increased the thermal conductivity of the material significantly, because water has a thermal conductivity of more than 10 times that of most insulating materials.

Graphs a and b of Figure 7 for the thermal conductivity of bagasse specimens that were air-dried and those with 5% moisture added to air-dried bagasse are almost identical in shape. Graph b, for the 5% moisture specimens, shows higher values than graph a for the air-dried specimens by a constant difference of about 0.0056 W/m·K, or an average increase of 17% in the thermal conductivity value.



a. 52 mm thick Bagasse fiber—air dry
b. 52 mm thick Bagasse fiber—5% moisture by weight added to air dry fiber

Figure 7 *Thermal conductivity as a function of density experimental results—Bagasse.*

There was no indication of moisture loss from the specimens. Comparisons of the weight of the specimens before and after testing were all within ±0.05%. Visual checks for moisture migration indicated that the 5% moisture was absorbed within the bagasse. There was no indication of moisture condensation on the cold surface of the specimen.

TABLE 6 **Experimental Results for 5% Moisture by Weight Added to Air Dried Bagasse—Atmospheric Pressure (14% Total Moisture by Weight)**

Density (kg/m^3)	Thermal Conductivity (W/m·K)
48	0.0374
56	0.0333
62	0.0322
65	0.0317
70	0.0322
80	0.0325
90	0.0348
110	0.0406

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