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Full Length Research Paper

Experimental investigation of the influence of air conduction on heat transfer across fibrous materials

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Accurate prediction of the effective thermal conductivity of loose fill fibrous building thermal insulation remains a challenging issue to date. Most researchers considered the complex problem of heat transfer across a fibrous material to be the sum of heat transfer due to air conduction, solid conduction and radiation for which general empirical relationships were developed from reliable thermal conductivity tests. In this study, an experimental investigation of this hypothesis was undertaken by removing the air from a porous material, hence, theoretically leaving heat transfer due to solid conduction and radiation only. This hypothesis was tested by conducting steady state thermal conductivity measurements under vacuum conditions for coconut fiber and sugarcane fiber specimens. Test results indicated an average difference between the thermal conductivity at atmospheric conditions and under vacuum conditions of 0.0279 and 0.0231 W/m.K for coconut fiber and sugarcane fiber, respectively, over the density range tested. The experimental results were in agreement with the widely expressed opinion that air behaves as an independent individual contributor to the overall effective thermal conductivity of a loose fill fibrous material.

Key words: Fibrous insulation, thermal conductivity, loose fill insulation, effective thermal conductivity, air conduction.

INTRODUCTION

Fibrous materials or those which can be readily reduced to fibers represent one of the most important raw products for the manufacture of fibrous insulating materials. Due to the high thermal insulating properties and lightweight, the potential of fibrous insulation is far reaching, for Ceramic fiber insulation has been selected as the primary thermal protection system for the space shuttle and has also found application in other re-entry vehicles (Linford et al., 1974; Paul and Diller, 2003).

Design studies for the application of fibrous insulation requires accurate data on the thermal conductivity of the fibrous materials and well established laboratory techniques for measurement. Therefore, future development in fibrous insulation depends to a large extent on the knowledge of insulating properties of the materials (Stephenson and Mark, 1961).

Many researchers have developed and analyzed theoretical models to simulate the heat transfer across fibrous materials. The underlying conclusion in each case was that there are three main modes of heat transfer across a fibrous material; that is, gas conduction, solid conduction, and radiation. The extent to which each mode of heat transfer contributed to the total heat transfer depended on variables such as effective density, material property, arrangement of fibers, and moisture content. This made the theoretical analysis for the effective thermal conductivity a complex problem (Stephenson and Mark, 1961; Cui et al., 2011; Finck, 1930; Bankvall, 1973; Wang and Pan, 2008).

Overview

Thermal conductivity of fibrous materials is usually measured under steady state conditions. Because of the

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complex interactions of many modes of heat transfer, the thermal conductivity or effective thermal conductivity is determined experimentally (Wang and Pan, 2008; Bhattacharya, 1980; Cheung et al., 1962; Lei and Zhu, 2010).

The main objective in developing more effective insulating materials is to reduce the influence of the major modes of heat transfer. For this purpose, it is necessary to investigate the influence of the various modes of heat transfer (that is, solid conduction, air conduction and radiation) on the overall thermal conductivity.

One method of analysis was to treat the different heat transfer mechanisms separately. Fibrous materials were treated as a combination of a solid phase and a gas phase and theoretically the total effective heat transfer across the fibrous material was the sum of the heat transfer due to solid conduction, air conduction and radiation. Many researchers (Cui et al., 2011; Finck, 1930; Bankvall, 1973; Wang and Pan, 2008; Bhattacharya, 1980; Cheung et al., 1962; Lei and Zhu, 2010; Stops, 1974; Rowley et al., 1952) have attempted to analyze the individual modes of heat transfer and provide mathematical models for each mode. Although the methods of analysis differed in these studies, the general conclusions were the same.

The main conclusions could be summarized as follows:

1. Conduction due to air was a major contribution to the total thermal conductivity over the density range that included the critical density.
2. Radiation was of greatest importance for low density materials (lower than the critical density) and resulted in high thermal conductivity values in this range.
3. Conduction in solid was important in high-density materials (above the critical density) and resulted in an increase in the thermal conductivity in this range.
4. Increasing the mean temperature of a material gave an increase in its effective thermal conductivity value. This was especially noticeable at lower density values where radiation was the dominant mode of heat transfer.
5. The general distribution of each mode of heat transfer was represented in a combination as shown in Figure 1.

Theory

The graphical representation in Figure 1 (Manohar, 1991) shows that the apparent thermal conductivity of fibrous insulation followed a characteristic hooked shape graph with a minimum thermal conductivity at some critical density (Paul and Diller, 2003; Stephenson and Mark, 1961; Cui et al., 2011; Finck, 1930; Rowley et al., 1952). Many researchers developed and theoretically analyze models to simulate heat transfer across fibrous materials. The underlying conclusion in each case was that there are three main modes of heat transfer, namely, gas conduction, solid conduction and radiation. The extent to which each mode contributed to the total heat transfer depended on variables such as effective density, material properties, arrangement of fibers and moisture content. This made the theoretical analysis of the effective thermal conductivity a complex problem. Models developed to predict the effective thermal conductivity ranged from simple equations such as

$$\lambda = 4.5\sigma T_m^3 \left(\frac{d}{\delta_r}\right) \quad \text{(Hager and Steer, 1967)}$$

to more complex equations such as

$$\lambda = \alpha \left[\varepsilon_p \lambda_g + (1-\varepsilon_p)\lambda_s\right] + (1-\alpha)\frac{\lambda_s \lambda_g}{\varepsilon_g \lambda_s + (1-\varepsilon_g)\lambda_g}$$

(Bankvall, 1973).

Regardless to simplicity or complexity of model, it was accepted that heat transfer due to air conduction is a major contributor since in low density fibrous insulation materials air accounted for over 75% of the material space. Another observation was that radiation heat transfer was high at low density and decreased exponentially to a negligible value at the critical density (Cui et al., 2011; Finck, 1930; Bankvall, 1973; Wang and Pan, 2008; Bhattacharya, 1980; Cheung et al., 1962; Lei and Zhu, 2010; Stops, 1974; Rowley et al., 1952; Wang, 2007; Verschoor et al., 1952; Hager and Steer 1967; Manohar, 1991).

Assuming the aforementioned conclusions were true, then by subtracting the contribution due to air from the total thermal conductivity value will leave the thermal conductivity contribution due to radiation and solid conduction at low density. At high density where the heat transfer due to radiation was negligible, the only mode contributing to the heat transfer would be the solid constituent.

TEST APPARATUS AND PROCEDURE

To test the validity of the hypothesis thermal conductivity, measurements were conducted with two large 1 × 1 m water activated constant temperature plates (Figure 2) (Manohar, 1991). The constant temperature plates were designed and built to meet standards set by B.S.874 and the test apparatus was calibrated according to ASTM and NIST specifications for standard reference material 1451. Each plate was monitored with 14 k-type thermocouples via a Cole Parmer temperature monitor with an accuracy of ±0.3°C and a resolution of 0.1°C. The heat flow was measured with a 120 × 120 × 4 mm thermopile linked to a k-Therm Heat Flow Meter. The k-Therm instrument had a heat flux range of ±199.9 W/m^2, conductance range of ±19.99 W/m^2.K and an accuracy of ±3%. Instantaneous values of heat flux, cold face temperature and hot face temperature was recorded every 20 s and the instrument calculated and printed instantaneous and average values of conductance, hot face and cold face temperatures. Calibration tests indicated accuracy within 1.38% of the NIST certified value for SRM 1451 and repeatability within 2.5%. NIST specified that the thermal conductance value for this SRM was expected to be within 3% of the computed certified value.

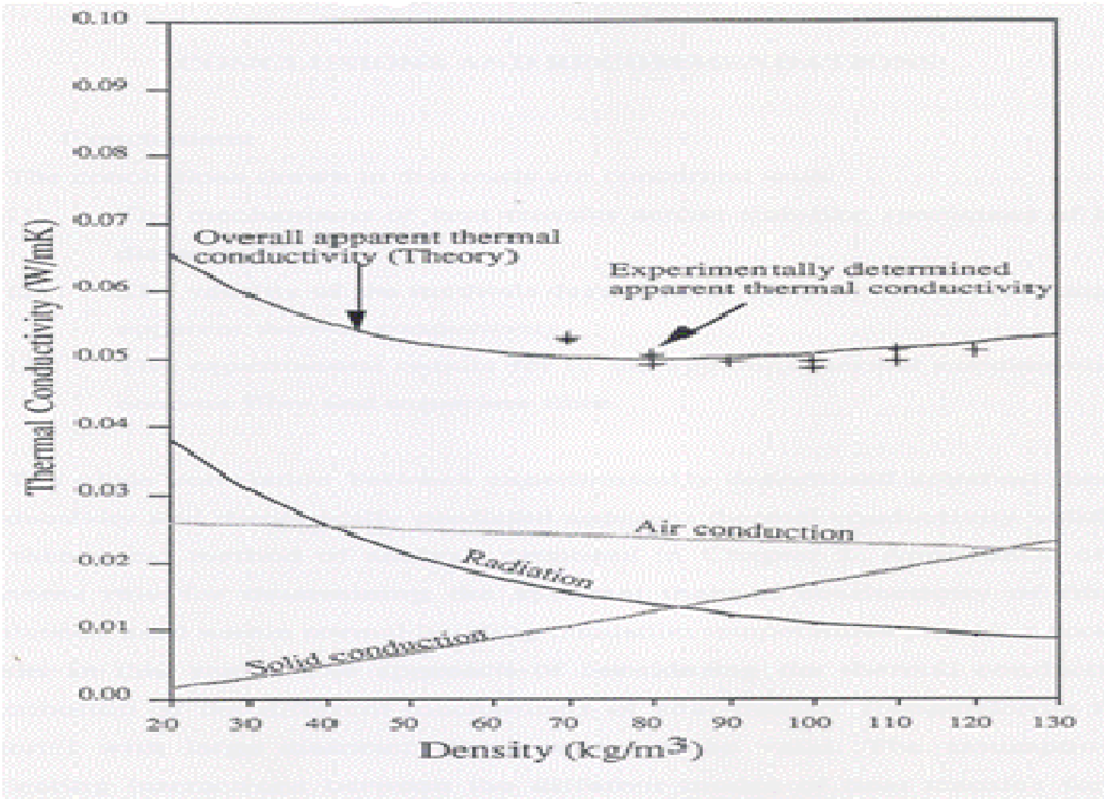

Figure 1. Apparent thermal conductivity of sugarcane fibre (Manohar, 1991).
SUGARCANE FIBRE: - Theoretically determined thermal conductivity contribution due to air conduction, solid conduction, radiation and apparent thermal conductivity. Plotted points (+) are the experimentally determined apparent thermal conductivity.

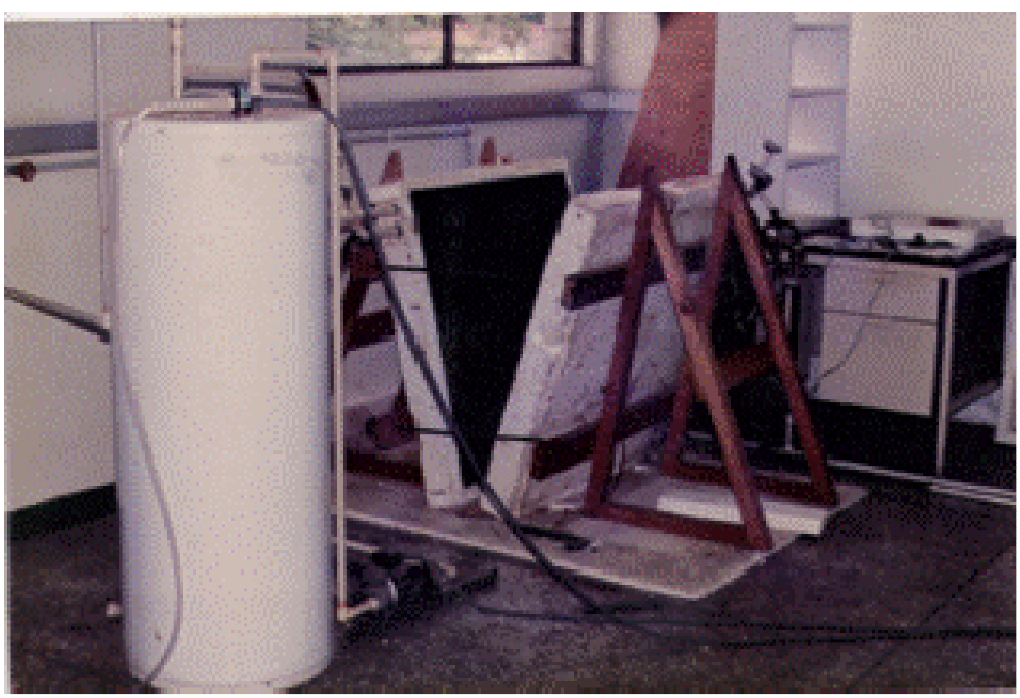

Figure 2. Steady state cold/hot plate apparatus.

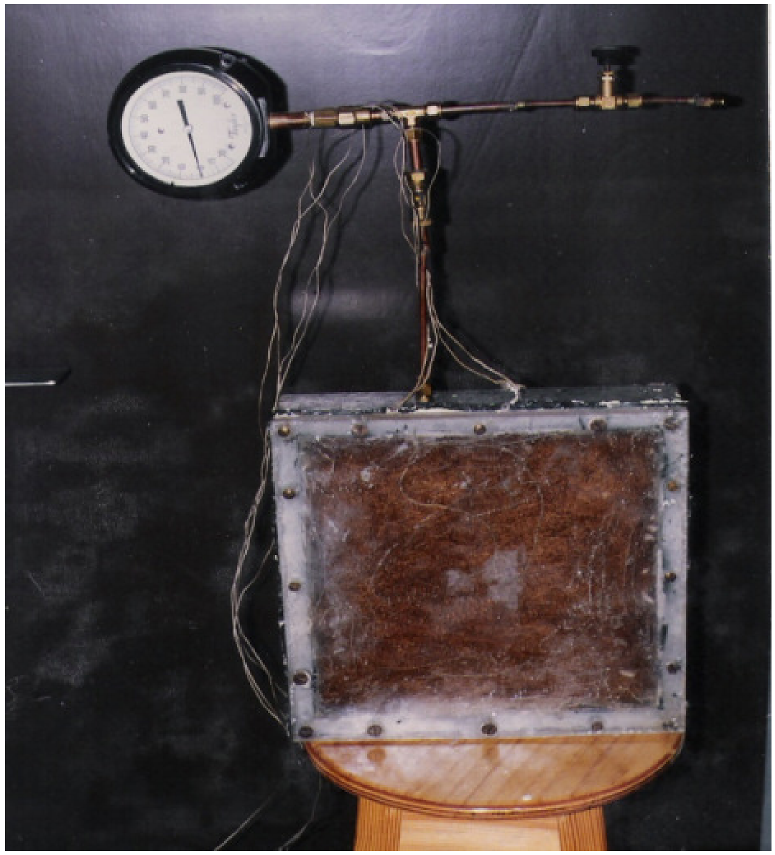

Figure 3. Vacuum chamber showing vacuum gauge, sight glass and thermocouple wires.

Vacuum test apparatus

To investigate the effect of air on thermal conductivity of loose fill fibrous material, a vacuum chamber with internal dimensions 300 × 300 × 46 mm was constructed from 25 mm thick Plexiglas, Figure 3 (Rohm Hass Company, 1990). The chamber had a removable cover secured by bolts. A vacuum gauge and a sight glass were mounted on the side of the chamber at the vacuum pump outlet.

Procedure

Ten specimens at each density for coconut fiber and sugarcane fiber in the density range 30 to 115 kg/m^3 and 60 to 115 kg/m^3, respectively, were tested under vacuum conditions and under atmospheric conditions. For coconut fiber and sugarcane fiber specimens lower than 30 and 60 kg/m^3, respectively, settling under gravity occurred. Hence, minimum test density of 30 and 60 kg/m^3 was used for coconut and sugarcane fiber, respectively. The vacuum chamber with sample inside was treated as a normal slab-like test specimen for the cold plate hot plate apparatus. For air-dried specimens under normal atmospheric conditions the slab-like specimens were formed with the fibrous material placed in a specimen holder of size 600 × 600 × 52 mm. After the setup of each test specimen, the apparatus was operated for 48 h to establish equilibrium conditions. The data acquisition unit and heat flow meter were then switched on. For test specimens under vacuum conditions, the vacuum pump was also switched on at this point. The test rig was operated under these conditions for another 24 h and equilibrium conditions verified when four consecutive readings at one hour intervals from the heat flux transducer showed a maximum spread of 1% between the highest and lowest values. These criteria satisfied conditions outlined in BS 874. Final steady state readings were recorded at 20 s intervals for one hour and the average values for this period were used to compute the effective thermal conductivity.

RESULTS

For the ten specimens at each test density thermal conductivity test was conducted under vacuum and atmospheric pressure conditions. The highest and lowest test values were discarded and the average of the other eight test values calculated. The average thermal conductivity values at each test density were tabulated and are shown as the experimental results for the vacuum tests and for test under atmospheric conditions for coconut fiber and sugarcane fiber on Tables 1 and 2, respectively.

DISCUSSION

Heat transfer across fibrous materials has always been a

Table 1. Experimental results for coconut fiber.

Mean test temperature	39℃
Mean fiber diameter	0.255 mm
Air dried moisture content	9% by weight

Density (kg/m^3)	Thermal conductivity vacuum test (W/m.K)	Thermal conductivity atmospheric pressure test (W/mK)	Difference between thermal conductivity (W/mK)
30	0.0640	0.0966	0.0326
40	0.0464	0.0775	0.0311
50	0.0400	0.0702	0.0302
60	0.0370	0.0634	0.0264
70	0.0340	0.0606	0.0266
80	0.0314	0.0591	0.0277
85	0.0320	0.0585	0.0265
100	0.0334	0.0594	0.0260
110	0.0350	0.0612	0.0262
115	0.0376	0.0632	0.0256

Table 2. Experimental results for sugarcane fiber.

Mean test temperature	39℃
Mean fiber diameter	0.28 mm
Specimen thickness	52 mm

Density (kg/m^3)	Thermal conductivity vacuum test (W/m.K)	Thermal conductivity atmospheric pressure test (W/mK)	Difference between thermal conductivity (W/mK)
60	0.0265	0.0551	0.0286
70	0.0266	0.0532	0.0266
80	0.0276	0.0492	0.0216
90	0.0279	0.0495	0.0216
100	0.0299	0.0512	0.0213
110	0.0329	0.0542	0.0213
115	0.0343	0.0553	0.0210

complex problem to analyze due to the many different, simultaneous heat transfer mechanisms. The theoretical analysis suggested (Linford et al., 1974; Paul and Diller, 2003; Stephenson and Mark, 1961; Cui et al., 2011; Finck, 1930; Bankvall, 1973; Wang and Pan, 2008; Bhattacharya, 1980; Cheung et al., 1962; Lei and Zhu, 2010; Stops, 1974; Rowley et al., 1952; Wang, 2007; Verschoor et al., 1952; Hager and Steer, 1967; Manohar, 1991) sought balance between complex mathematical analysis, practical observations and experimental results to develop specific empirical relationships for heat transfer by the different modes across a loose fill fibrous insulating material. However, no work reported experimental verification of the individual modes of heat transfer contributing to the overall effective thermal conductivity.

This study was geared towards verifying the validity of the widely accepted theory that suggested the heat transfer to be a combination of air conduction, solid conduction and radiation. Hence, by removing the air component in the material, thereby removing the heat transfer contribution due to air conduction, should theoretically leave the heat transfer contribution due to solid conduction and radiation only.

Tests were conducted on coconut and sugarcane fiber specimens under atmospheric and vacuum conditions at a mean test temperature of 39℃. Experimental results on Tables 1 and 2 showed an average difference between the thermal conductivity at atmospheric conditions and under vacuum conditions to be 0.0279 and 0.0231 W/m.K for coconut fiber and sugarcane fiber, respectively. The thermal conductivity of air at 39℃ was interpolated to be

0.027 W/m.K. This indicated a 3 and 14% difference between the average values for coconut fiber and sugarcane fiber, respectively, which was in agreement with the widely accepted hypothesis.

The difference in thermal conductivity was largest at the lowest density for both materials. Values of 0.0326 and 0.0286 W/m.K for coconut fiber and sugarcane fiber, respectively, both greater than the thermal conductivity of air was observed. Also, as density increased, the difference in thermal conductivity column on Tables 1 and 2 showed a general decrease for both materials. This trend may be due to the materials at low density has larger pore spaces as a result of the larger volume composition of air. In this case, the air may have had heat transfer by both conduction and convection modes thereby contributing more heat transfer due to the air component. As density increased, the pore spaces decreased and the heat transfer from the air component was mainly due to conduction only as convection would have been restricted in the small void spaces. The vacuum test results for sugarcane fiber showed an increase in thermal conductivity with increase density. Based on the widely accepted hypothesis, removal of the air component resulted in heat transfer contribution by solid conduction and radiation only. Therefore, as density increased, the amount of solid fiber increased and hence the effective conductivity increased. The effect of the exponentially decaying radiation component was negligible in this case as the sugarcane fiber density was close to the optimum minimum overall effective thermal conductivity. The vacuum test results for coconut fiber showed a decrease and then an increase in thermal conductivity with increase density. Again, removal of the air component resulted in heat transfer contribution by solid conduction and radiation only; however, in the case of coconut fiber at the low densities, the contribution from radiation was significant. Based on the widely accepted hypothesis, the radiation contribution decreased to negligible values as the density approached the optimum minimum overall effective thermal conductivity. At the higher test densities, the vacuum test results for the coconut fiber specimens also showed increase in thermal conductivity with increase density.

In general, this study showed that air conduction can be considered as a separate and independent constituent in the heat transfer across loose fill fibrous materials and supported the general hypothesis that the overall effective heat transfer across fibrous materials is a combination of radiation, solid conduction and gas conduction.

Conclusions

1. The difference in the thermal conductivity between specimens under atmospheric conditions and specimens under vacuum conditions was close to the thermal conductivity of air.
2. At low density, the thermal contribution due to air was higher and decreased as specimen density increased.
3. The experimental results were in agreement with the widely expressed opinion that air behaves as an independent individual contributor to the overall effective thermal conductivity of a loose fill fibrous material.

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