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EXPERIMENTAL STUDY OF HEAT TRANSFER IN ATTICS WITH A SMALL-SCALE SIMULATOR

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ABSTRACT

An experimental study concerned with different modes of heat transfer in fibrous and cellulose insulating material is presented. A series of experiments were conducted using an attic simulator to determine the effects of ventilation on attic heat transfer and the effect of infrared radiation on the thermal conductivity of insulation and on attic heat transfer. All the tests were performed at steady-state conditions by controlling the roof deck temperature. Tests were performed for insulation thicknesses between 1 in (25 mm) and 7 in (178 mm) and roof deck temperatures between 145 F (63 °C) and 100 F (36 °C).

The temperature profiles were measured by placing thermocouples at various levels within the insulation. The profiles for the cellulose insulation were linear. The profiles within the fibrous insulation were nonlinear due to the effect of infrared radiation. Heat fluxes were measured through different insulation thicknesses and for different roof temperatures. It was found that a radiant barrier such as aluminum foil can reduce the heat transfer from the roof to the attic floor by as much as 50 %.

Experiments were also conducted when ventilating the attic by means of a fan. The hot side temperature of the fibrous insulation was reduced by 5 to 9 F (3 to 5 °C) with ventilation; however, the effects of infrared radiation were still dominant in fibrous insulation even with ventilation. Compared to the nonventilation case, the heat flux through the floor of the attic was reduced by about 16 %.

INTRODUCTION

Cooling energy required for residential and commercial buildings in most southern states is often the largest single contributor to energy use in these buildings. The fraction of incident solar energy absorbed by the roof of an attic can significantly impact the summer cooling load requirements. In the summer, incident solar radiation can cause this attic indoor–outdoor temperature differential to be several times the actual indoor–outdoor temperature differential. It has been reported that in lightweight fibrous insulation, such as building insulation, thermal radiation could account for as much as 30 % of the total heat transfer even at moderate temperatures (Bankvall 1973; Pelanne 1977).

Heat transfer in fibrous insulation has been a subject of importance because of its wide application in residential housing. A substantial savings both in cost and overall energy consumption can be achieved if even a small improvement is made on insulation effectiveness. Therefore, a better understanding of the modes and characteristics of heat transfer in fibrous insulation is essential.

The primary source of heat gain in attics is the solar energy absorbed by the roof. Previous research on the measurement of the thermal resistance of fibrous insulation materials used two impermeable boundaries, one hot and one cold. However, for some applications the above test

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conditions would be invalid. For example, in an attic there is only one impermeable surface instead of two. Therefore, the effect of such external factors as air temperature and environmental radiation temperature were neglected.

All the primary modes of heat transfer exist in fibrous insulating materials: conduction, convection, radiation, and mass transfer. The combined modes make the formulation of the energy transfer problem quite complicated. Quantitative computations are often severely limited due to the lack of theories describing certain heat transfer phenomena and/or the unavailability of certain heat transfer properties of the insulation.

BACKGROUND

The principal source of summertime attic heat is direct sunlight on the roof. Solar heat from the roof is transmitted through the roof deck, radiating much of this heat into the attic space. The air inside the attic, which is in contact with the underside of the roof and the top of the ceiling insulation, becomes heated by natural convection. In an unventilated attic, the roof sheathing may reach a temperature in excess of 160 F (71 °C) and the attic floor, 150 F (66 °C), when the outside temperature is 90 F (32 °C) (Wolfert and Hinrichs 1974; Fairy et al. 1983). The ceiling acts like a "*hot plate*," not only warming the room, but also radiating some of the heat to the occupants.

The results of the various experimental tests on the effects of ventilation showed that the use of powered ventilation for flushing the attic during the cooling season is not economically justified (Burch and Treado 1979; Brewster and Arkfeld 1979; Lorne and James 1979; Dutt and Harrje 1979; Gort and Siu 1979; Clark 1979; and Peavy 1979). Three identical houses in Houston, Texas, were extensively instrumented for measuring air–conditioner energy consumption and ceiling and duct heat gain rate (Burch and Treado 1979). They found that in two of the houses, the addition of power venting to soffit venting of the attics, which had ceiling insulation of 4 in (102 mm) and 6.5 in (165 mm), respectively, reduced the temperature by 10 F (5.6 °C) at an outdoor temperature of 95 F (35 °C). This reduced the ceiling heat gain rate by 23 % and 25 % for the two houses, which was approximately 5.7 % of the total cooling load at the maximum load condition. In the case of power venting at maximum load condition, the reduction in energy consumption of a properly sized air conditioner was calculated to have been offset by the energy consumption of the power vent. When the effect of reduced ceiling and duct heat gain was considered over a period of a day, attic ventilation was found to produce less than a 3 % reduction in daily cooling loads for the test houses.

Radiation exchange in attics has been recognized for many years as a significant mode of heat transfer in the attic energy balance. Burch at the National Bureau of Standards has several papers on attic heat transfer from experimental studies (Burch and Treado 1979; Burch 1979; Burch 1980). Headrick and Jordan (1969) and Kusuda et al. (1981) have used both analog and digital methods to predict attic heat transfer. All these studies, however, treat the radiatant heat transfer as a surface phenomenon and do not account for penetration into the insulation. Joy (1958) used a highly reflective aluminum foil on top of fibrous insulation in a ceiling and found that the thermal resistance of the insulating system was significantly increased. Recent studies at the Florida Solar Energy Center (FSEC) have shown the penetration of radiation from a hot roof deck may produce an effective R-value appreciably lower (50 %) than the measured value in the guarded hot plate rating test (Fairy et al. 1983). Their studies indicated that 90 % of the heat transfer in attics occurs via radiation and only 10 % of it is due to natural convection when the roof is sunlit. The FSEC's study had several shortcomings: the experiments were not conducted in steady–state conditions, the study did not include the effects of ventilation air, and the tests were qualitative only and were not conclusive in helping to model the heat transfer phenomena. There is a need for additional study of attic heat transfer phenomena under tightly controlled conditions of the roof temperature and ventilation rate.

The literature review showed that radiation can be a major source of attic heat gains. Even though some investigations have been conducted to study the effects of infrared radiation on fibrous insulation, these studies have some significant experimental limitations: small test facility, non–steady–state testing, and no ventilation. These studies have also not investigated the effect of infrared radiation on high density cellulose insulation. Data showing effects of infrared radiation on thermal conductivity, heat transfer, and temperature profiles within insulations of various thicknesses are required to accurately estimate attic heat gains. The effectiveness of a radiant barrier to reduce the heat flux has been proved by FSEC (Fairy et al. 1983) and Joy (1958). More knowledge of the effect of radiant barriers in reducing the influence of the infrared radiation and the effect on overall performance of the insulation system are needed.

A considerable amount of work has been done on the ventilation of attic space. Most of the studies indicated that forced ventilation was not economically feasible. Hence, only ventilation rates comparable to natural ventilation are required to study the ventilation effect on the attic heat transfer.

EXPERIMENTAL SETUP AND PROCEDURE

A 4 ft x 4 ft x 3 ft (1220 mm x 1220 mm x 914 mm) box, with aluminum foil covering the inside walls, was constructed from 0.75 in (19 mm) plywood. Two 2 in x 6 in (5.1 mm x 15 mm) boards were installed on the 0.5 in (13 mm) sheetrock floor (ceiling) and were secured to the 0.75 in (19 mm) plywood to simulate the bottom surface of an attic. The side insulation consisted of multiple layers of expanded polystyrene 1 in (25 mm) board stock insulation with total total R–value of 47 h·ft·F/Btu (89 K/W) on the four sides and top of the simulator (Figure 1).

Four heat flux meters were installed on the bottom surface to measure the ceiling heat flux. The flux meters were constructed of 0.38 in (9.5 mm) bakelite placed between two 0.38 in (9.5 mm) thick aluminum plates of 6 in x 6 in (152 mm x 152 mm). The thermocouples were placed on the top surface between the bakelite and the aluminum and on the bottom of the bakelite between it and the other aluminum plate. Because the thermal conductivity of the bakelite was known, the heat flux was computed by measuring the temperature drop across the bakelite. The heat flux meters were attached to the gypsum board by nylon bolts to minimize heat transfer through the bolts.

A 4 ft x 4 ft x 0.25 in (1220 mm x 1220 mm x 6.4 mm) aluminum sheet heated by a 555 watt, 110V electric coil was mounted on the top of the box. The coil was supported in a 4 ft x 4 ft x 6 in (1220 mm x 1220 mm x 152 mm) chamber just above the aluminum plate. The aluminum plate was maintained at a constant temperature with the aid of temperature controller. Thermocouples were placed at various places inside the box to perform the energy balance on the simulator.

Data Acquisition

A 60 channel data logger was used to scan the various thermocouples at required time intervals. A printer, interfaced to the data logger, recorded the channel temperatures. All the channels of the data logger were verified for consistency and accuracy.

Materials

An aluminum film radiation reflector was used as a radiant barrier. The emissivity of the radiation reflector was 0.02 (Incropera and Dewitt 1981). The cellulose insulation used was of density 2.6 lb/ft^3 ($41.6\ kg/m^3$) with an R-value of 3.9 h·ft·F/Btu·in (89 K/W at 70 F). Fibrous insulation was of density 0.75 lb/ft^3 ($12.0\ kg/m^3$) and R-value of 3.1 h·ft·F/Btu·in (70.5 K/W at 70 F).

EXPERIMENTAL RESULTS AND ANALYSIS

To determine the effects of the attic ventilation on the attic heat transfer and the effects of infrared radiation on the thermal conductivity of the insulation system and the attic heat transfer, a series of tests were conducted. All the tests were performed at steady–state conditions by controlling the roof deck temperatures. Tests were performed for insulation thicknesses between 1 in (25 mm) and 7 in (178 mm) and roof deck temperatures between 145 F (63 °C) and 100 F (38 °C). The thermocouples were placed at two different locations at the same height, and the average of the two values was used to plot the graphs. The thermocouples used to measure the hot side of the insulation were shielded. The insulation systems included:

- Cellulose insulation (1 in and 2 in)
- Fibrous insulation (1 in – 7 in)
- Reflective foil
- Cellulose insulation with reflective foil
- Fibrous insulation with reflective foil
- Fibrous insulation with controlled ventilation.

TEMPERATURE PROFILES

Profiles within Cellulose Insulation

The temperature profiles within the 2 in (51 mm) thick cellulose insulation are shown in Figure

2 . The temperature profile is linear, which implies that the infrared radiation only interacts with the top surface of the cellulose insulation and does not penetrate into the insulation. Because of the high density of cellulose, it acts as a solid rather than a porous media.

Profiles within Fibrous Insulation

Figures 3 and 4 show the temperature profiles * within the fibrous insulation 3.5 in (89 mm) and 7 in (178 mm) thick, respectively. Both the figures show the profiles to be nonlinear due to the influence of the infrared radiation at both the upper and lower surfaces of the fibrous insulation. The infrared radiation tends to lower the resistance of the insulation. Hence, the temperature profiles become nonlinear at the ends where the influence of the infrared radiation is maximum. Figure 5 shows the comparison of temperature profiles within 1 in (25 mm), 2 in (51 mm), and 3.5 in (89 mm) thick fibrous insulation at a roof temperature of 127 F (53 °C). It is evident from Figure 5 that for the same roof temperature and different insulation thickness the nonlinearity increases with the thickness of the insulation. To highlight the nonlinearity of the profile and to show how the nonlinearity increases with roof temperature, the difference between measured temperature, 'T', and the temperature for a linear profile, 'T_{Lin},' is plotted versus the thickness of the sample in Figure 6 . Where

$$T_{Lin,X} = \frac{(T_{cold} - T_{hot}) \times X}{(\text{thickness of insulation})} + T_{cold} \tag{1}$$

Profiles for Insulations with Reflective Foil

Figure 7 shows the temperature profile versus the roof temperatures for 3.5 in (89 mm) thick fibrous insulation with reflective barrier. The foil backing is on the hot side of the insulation system. Because of the radiant shield, the effects of infrared radiation are insignificant on the hot side of the insulation. The temperature profile is linear, and the average drop of the temperatures is 23 F (12 °C).

Profiles within Fibrous Insulation with Ventilation

Figure 8 shows the temperature profile for the 3.5 in (89 mm) thick fibrous insulation with ventilation. The ventilation rate is 0.5 cfm/ft^2 (0.0025 $m^3/s \cdot m^2$). Comparisons of the temperature profiles for 3.5 in (89 mm) fibrous insulation with ventilation and without ventilation are shown in Figure 9 for two different roof deck temperatures. Ventilation lowered the temperatures by 9 F (5 °C) at 111 F (44 °C) roof deck temperature and by 5.4 F (3 °C) at 127 F (53 °C) roof deck temperature, but it did not have any significant effect on the shape of the temperature profile within the insulation. The profile is still nonlinear as it is in the case without ventilation.

HEAT FLUX MEASUREMENTS

Heat Flux through Cellulose Insulation

Figure 10 shows the total heat flux through samples of thickness, 1 in (25 mm) and 2 in (51 mm), for cellulose insulation plotted as a function of the hot–plate temperature. The profiles of 1 in (25 mm) and 2 in (51 mm) thick insulation are linear.

Heat Flux through Fibrous Insulation

Figure 11 shows total heat flux through 1 in (25 mm), 2 in (51 mm), and 3.5 in (89 mm) thick fibrous insulation samples plotted versus the roof temperatures. All the heat flux profiles are linear. A comparison of heat flux through 1 in (25 mm) cellulose insulation with 1 in (25 mm) fibrous insulation shows that there is 15 % decrease of heat flux, although low–density fibrous insulation is affected by infrared radiation. At lower insulation thicknesses, the effects of radiation are not so apparent.

Heat Flux through Insulation with Reflective Foil

Figure 12 shows the reduction of heat flux (in percent) with 2 in (51 mm) thick cellulose insulation with reflective foil backing as compared to 2 in (51 mm) thick cellulose insulation. The resistance to heat flux of 2 in (51 mm) of cellulose insulation with reflective foil is 50 % greater than that of the 2 in (51 mm) thick cellulose insulation without reflective foil backing.

* Unless otherwise indicated, all the data points in the temperature profile in the fibrous insulation were joined by smooth curves passing through the maximum number of points

Figure 12 also shows the reduction of heat flux with 3.5 in (89 mm) thick fibrous insulation with reflective foil backing as compared to 3.5 in (89 mm) thick fibrous insulation. The resistance of the insulation system backed with reflective foil had twice the resistance of the insulation system without reflective foil backing.

Heat Flux through Fibrous Insulation with Ventilation

Figure 13 shows the comparisons of heat flux for 3.5 in (89 mm) fibrous insulation with reflective foil, and 3.5 in (89 mm) fibrous insulation with and without ventilation. The change in the heat flux for 3.5 in (89 mm) fibrous insulation with ventilation as compared to nonventilation is about 16 %, as compared to the drop of more than 50 % for the same insulation system backed with aluminum foil.

CONCLUSIONS

The important conclusions of this experimental study are listed below:

Effects of Infrared Radiation on Fibrous Insulation

Effects of Infrared Radiation on the Temperature Profile. Experimental results showed the temperature profile within low–density fibrous insulation was nonlinear. The extent of nonlinearity was dependent on the temperature of the roof surface, and the thickness and the density of the insulating material. Nonlinearity increased with an increase in roof temperature and thickness of the insulation.

Effects of Infrared Radiation on Thermal Conductivity. Thermal conductivity for the fibrous insulating materials increased because of the influence of the infrared radiation. Infrared radiation reduced the resistance of the low–density porous, fibrous insulation, because one of the insulation surfaces was exposed to infrared radiation, thereby increasing the thermal conductivity. The thermal conductivity quoted by the manufacturers is obtained from results with the traditional guarded hot plate method at a mean temperature of 70 F (22 °C). The experimental results also showed an increase in thermal conductivity as the roof temperature increased. The thermal conductivities are show in Tables 1 through 3.

Effects of Infrared Radiation on Cellulose Insulation. Cellulose insulation was not affected by the infrared radiation because the density of the insulation is high. The fibrous insulation was found to be more effective than cellulose insulation for same thickness.

Effects of Radiation Shield. Highly polished aluminum foil was used as a backing on the hot side of the fibrous insulation and also by itself. When used as a backing on the 3.5 in (89 mm) thick fibrous insulation, it almost doubled the effective thermal resistance of the insulation and it reduced the heat flux in half when compared to the insulation alone. Table 4 shows the comparisons of heat flux for 3.5 in (89 mm) thick fibrous insulation and 3.5 in (89 mm) thick fibrous insulation with reflective foil backing at a 134 F (57 °C) roof deck. It was true even for the 2 in (51 mm) thick cellulose insulation. The temperature profile was linear in all cases where reflective foil was used as backing on the hot side of the insulation. The R-value in the case of the insulation with the reflective foil increased as much as 50 %.

Effects of Ventilation. Ventilation reduced the attic temperatures by 5 to 9 F (3 to 5 °C) but did not have any effect on the reduction of nonlinearity in the temperature profile within the insulation system. Heat flux reduced by about 15 % using ventilation air at 0.5 cfm/ft^2 (0.0025 m^3/sec·m^2), which corresponds roughly to the recommended natural ventilation in an attic (Wolfert and Hinrichs 1974). The 3.5 in (89 mm) thick fibrous insulation system with reflective foil backing on the hot side was more effective in increasing the resistance path and reducing the heat flux than 3.5 in (89 mm) thick fibrous insulation system with ventilation. Table 5 shows the comparisons of 3.5 in (89 mm) thick fibrous insulation with reflective foil backing and with 3.5 in (89 mm) thick fibrous insulation ventilation (0.0025 m^3 /sec·m^2) at 125 F (52 C) roof deck.

RECOMMENDATION

Most commonly used insulation systems in attics, in regions where cooling load is predominant are 7.25 in (180 mm) and 6 in (152 mm) [Waters 1984]. As reported in the earlier section, the effects of radiation start occurring at 134 F (57 °C) and above. Temperatures of 134 F (57 °C) inside attics are common in regions where the summertime load is predominant. Therefore, reflective foilfaced 3.5 in (89 mm) fibrous insulation could be used in place of 7.25 in

(180 mm) insulation with the same effective resistance. The study did not consider the reduction in emissivity of the reflective foil due to dust and other particles on the foil. It is recommended that the effect of dust on the performance of the reflective barrier be studied in order to provide reduction estimates of the long–term performance of reflective barriers.

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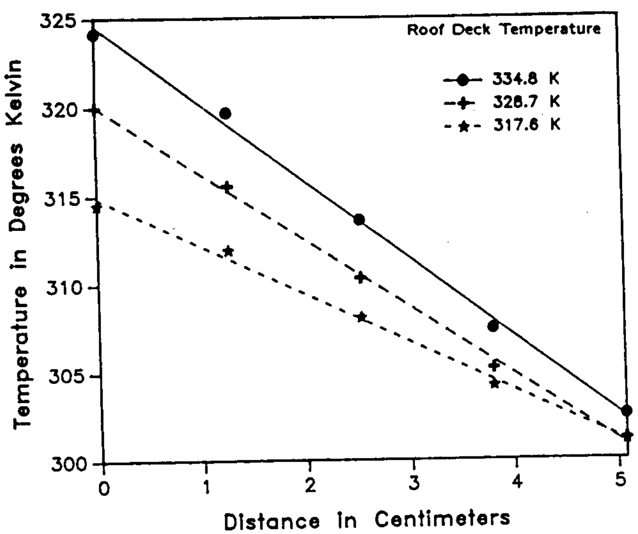

Figure 2. *Temperature profile within the 5.1 cm thick cellulose insulation at different roof temperatures*

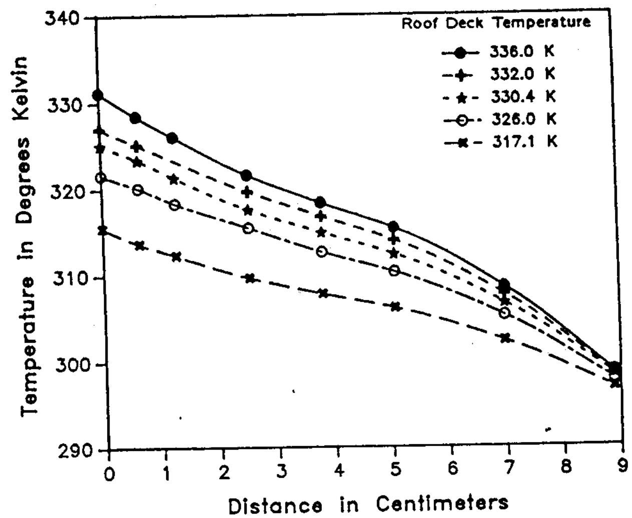

Figure 3. *Temperature profile within the 8.9 cm thick fibrous insulation at different roof temperatures*

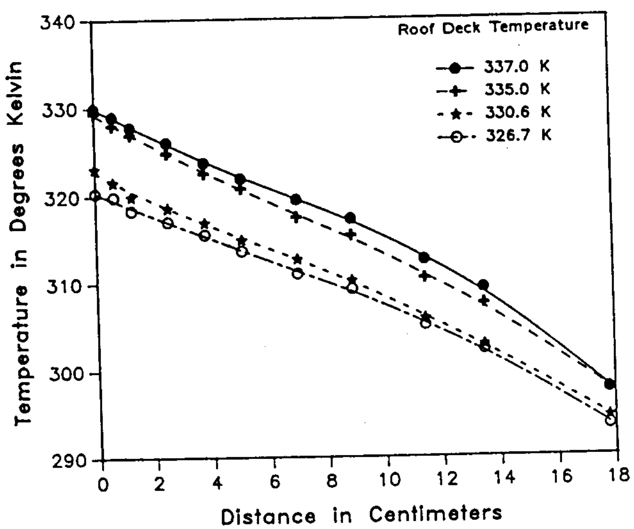

Figure 4. *Temperature profile within the 17.8 cm thick fibrous insulation at different roof temperatures*

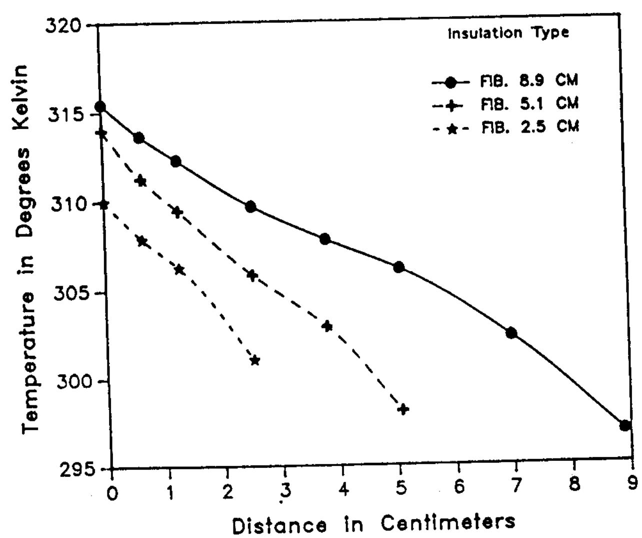

Figure 5. *Comparisons of temperature profiles for the 2.5 cm, 5.1 cm, and 8.9 cm thick fibrous insulation at a roof deck temperature of 318 K*

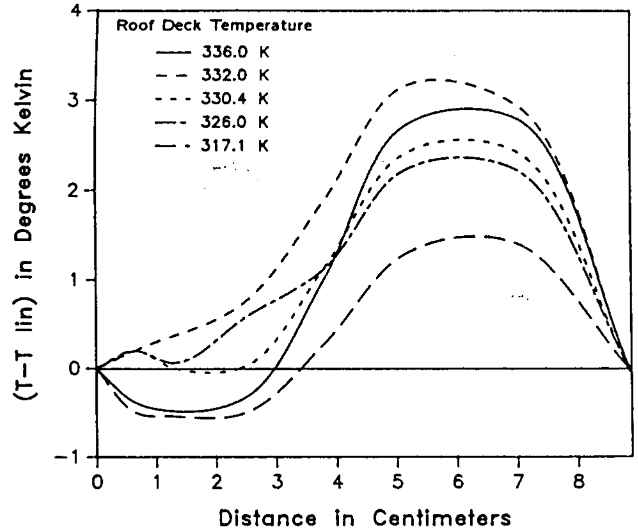

Figure 6. *Nonlinearity of the temperature profile within the 8.9 cm thick fibrous insulation for different roof temperatures*

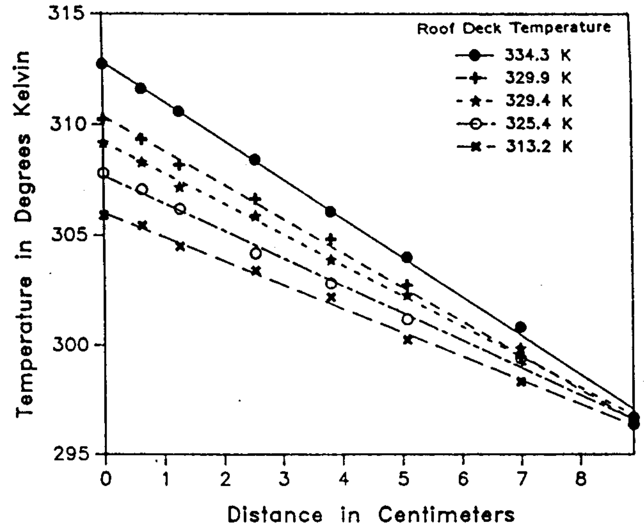

Figure 7. *Temperature profile for the 8.9 cm thick fibrous insulation system with reflective foil on the hot side of the insulation*

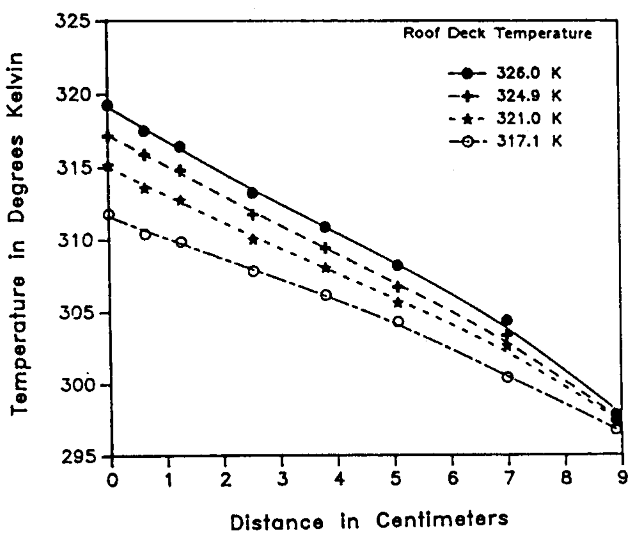

Figure 8. *Temperature profile for the 8.9 cm thick fibrous insulation with ventilation*

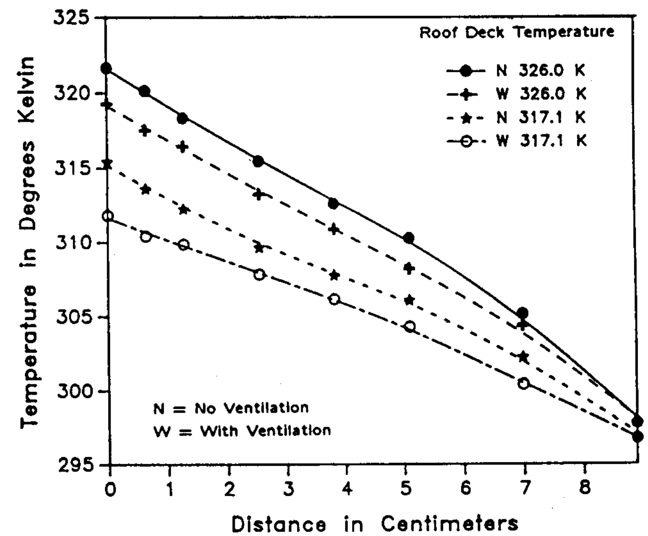

Figure 9. *Comparison of the temperature profiles for the 8.9 cm thick fibrous insulation with ventilation*

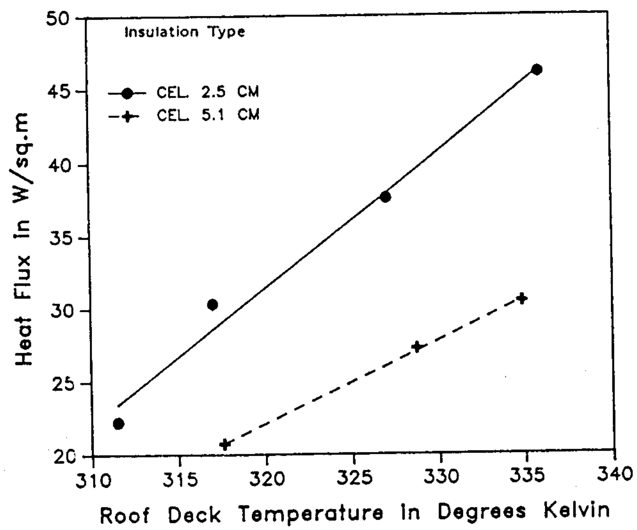

Figure 10. Heat flux vs. roof temperature for cellulose insulation

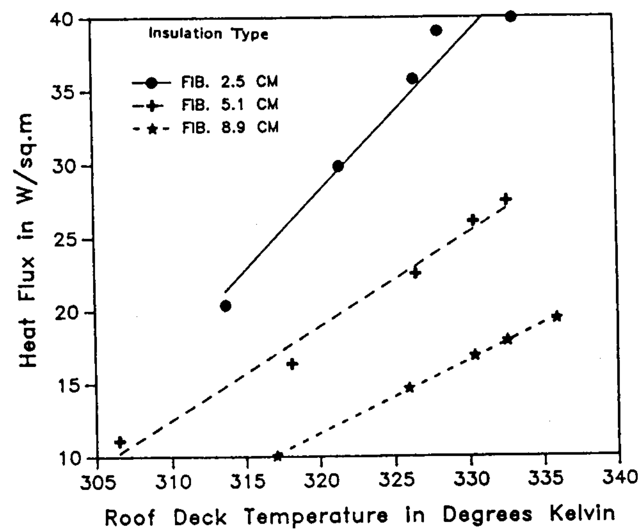

Figure 11. Heat flux vs. roof temperature for fibrous insulation

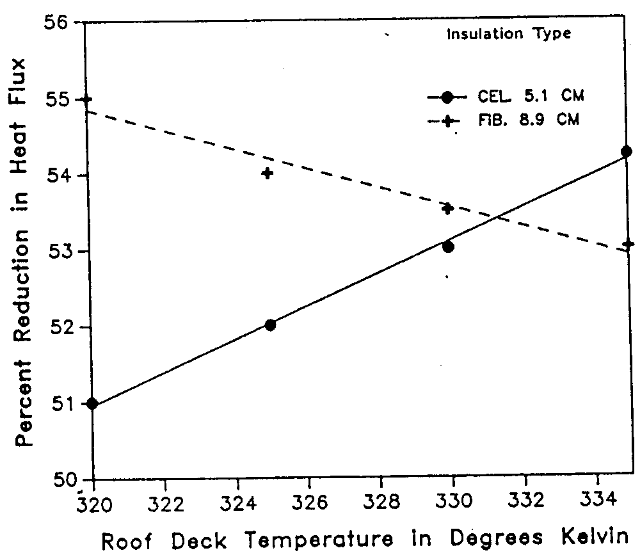

Figure 12. Percentage reduction in heat flux with a radiant barrier

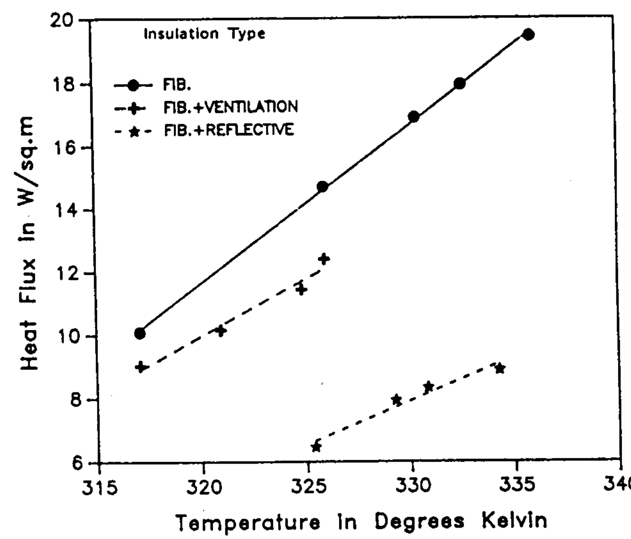

Figure 13. Comparison of heat fluxes with the addition of ventilation and a radiant barrier to 8.9 cm thick fibrous

Discussion

T.I. WETHERINGTON, Florida Power Corp., St. Petersburg, FL: What consideration is given to increased latent load on air conditioning that occurs with attic ventilation in attics with no vapor barrier?

S. KATIPAMULA and D. O'NEAL: We did not consider either the latent loads or the air-conditioner loads in this study.

J. CRAWFORD, The Trane Co., Tyler, TX: Did you attempt to control the simulated attic air temperature above the insulation as you varied the deck temperature and insulation system characteristics?

KATIPAMULA and O'NEAL: No, only the roof deck temperature was controlled in the simulator.

S. KAVANAUGH, University of Alabama, Tuscaloosa: Did you test the attic simulator with a simple membrane to limit convection? Such a test would determine how much heat transfer is due to convection in the fibrous insulation.

KATIPAMULA and O'NEAL: No. We did not use a membrane. We agree that such a test would be beneficial in determining how much of the reduction in heat transfer from the radiant barrier was due to a reduction in radiation and how much was due to reduction in convection in the fibrous insulation.

W.L. EASTES, R.D. GODFREY, M.F. MCBRIDE, Owens-Corning Fiberglas Corp., Granville, OH: Your paper presents some interesting and useful experimental data about heat transfer in an attic situation. We disagree, however, with the interpretation that radiation penetration is responsible for the non-linear temperature profile measured in the insulation. If radiation penetration were responsible, it would lead to a flattening of the temperature profile or a decrease in the temperature gradient at the hot and cold sides. In fact, the authors observed the opposite effect, an increase in the temperature gradient, or an improvement in the effective thermal conductivity, most pronounced at the cold side of the insulation. This effect is more likely due to the known increase in effective thermal conductivity of fibrous insulation with increasing temperature. The effect is much less when foil is placed on the insulation because it greatly reduces the mean temperature of the insulation, as observed by the authors. It should be noted that the highest temperature data in Figure 7, where foil was used, show a similar, but reduced, non-linear behavior. We have calculated the overall average effective thermal conductivity of the fibrous insulation from the authors' heat flux and temperature gradient data and found it to be the same for foil-faced and unfaced fibrous insulation to within experimental variation.