INFLUENCE OF INFRARED RADIATION ON ATTIC HEAT TRANSFER

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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 the insulation system and on attic heat transfer. All the tests were performed at steady state conditions by controlling the roof deck temperature. Calculations are performed for insulation thicknesses between 1 inch (2.54cm) and 6.0 inches (15.24cm) and roof deck temperatures between 145°F (62.78°C) and 100°F (36.78°C).

The temperature profiles within the insulation were measured by placing thermocouples at various levels within the insulation. The profiles for the cellulose insulation are linear. The profiles within the glass fiber insulation are non-linear due to the effect of infrared radiation. Also 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 flux significantly.

Experimental results were compared to a Three-Region approximate solution developed at Oak Ridge National Laboratories (ORNL). The model was in good agreement with experimental results.

INTRODUCTION

The energy required for cooling residential and commercial buildings in most southern states is significant. Heat transfer through the attic space is a major contributor to cooling loads. The fraction of incident solar energy absorbed by the roof of an attic will significantly impact the summer cooling load requirements. This is particularly true for regions that receive an abundance of solar radiation, such as most parts of the southern United States. In the winter, the maximum temperature differential between the house and the attic is limited by the indoor-outdoor temperature difference. In the summer, however, incident solar radiation can cause this attic indoor-outdoor temperature differential to be several times the actual indoor-outdoor temperature differential.

The importance of attic insulation and ventilation has been recognized for many years. It was not until the energy crisis developed in the early seventies that it became apparent that energy conservation through proper insulation and ventilation of attics would make a major contribution to saving energy in the cooling of houses.

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.

Previous research on the measurement of the thermal resistance of fibrous insulation materials used the guarded hot plate method. This method uses two impermeable boundaries, one hot and one cold. However, for some applications the above test conditions would be invalid, for example, in an attic there will be only one impermeable surface instead of two. Therefore, the effect of such external factors as air temperature and environmental radiation temperature should be considered.

All of the primary modes of heat transfer exist in fibrous insulating materials, and the coupled interaction of conduction, convection, radiation and mass transfer makes 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.

It is generally believed that thermal radiation is important only at high temperatures; however, it has been reported that in light weight fibrous insulation such as building insulation, thermal radiation could account for as much as 30 percent of the total heat transfer even at moderate temperatures [1,2].

BACKGROUND

HEAT TRANSFER MECHANISMS IN ATTICS

The principal source of summer time attic heat is direct sunlight on the roof. Sunlight is radiated heat, so even on a cloudy day there would be an appreciable amount transmitted to the roof. In the attic, the ratio of roof area to the enclosed volume is high; therefore the temperature is much more sensitive to solar radiation than in other structures. Solar heat from the roof is then 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 and by convection more and more of the attic air is heated. Gradually the temperatures increase until the entire attic, the roof, the insulation, the floor and the air become extremely hot. In an unventilated attic, the roof sheathing may reach a temperature in excess of 160° F (71.11°C) and the attic floor,150° F,(65.56°C) when the outside temperature is 90° F (32.22°C) [3,4]. The ceiling thus acts like a "*hot plate*", not only warming the room but also radiating some of the heat to the occupants.

VENTILATION OF ATTICS

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 [5-11]. Three identical houses in Houston, Texas were extensively instrumented for measuring air conditioner energy consumption and ceiling and duct heat gain rate [5]. 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″ and 6.5″ respectively, reduced the temperature by 10° F at an outdoor temperature of 95°F (35.0°C). This reduced the ceiling heat gain rate by 23 and 25 percent for the two houses, which was approximately 5.7 percent 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

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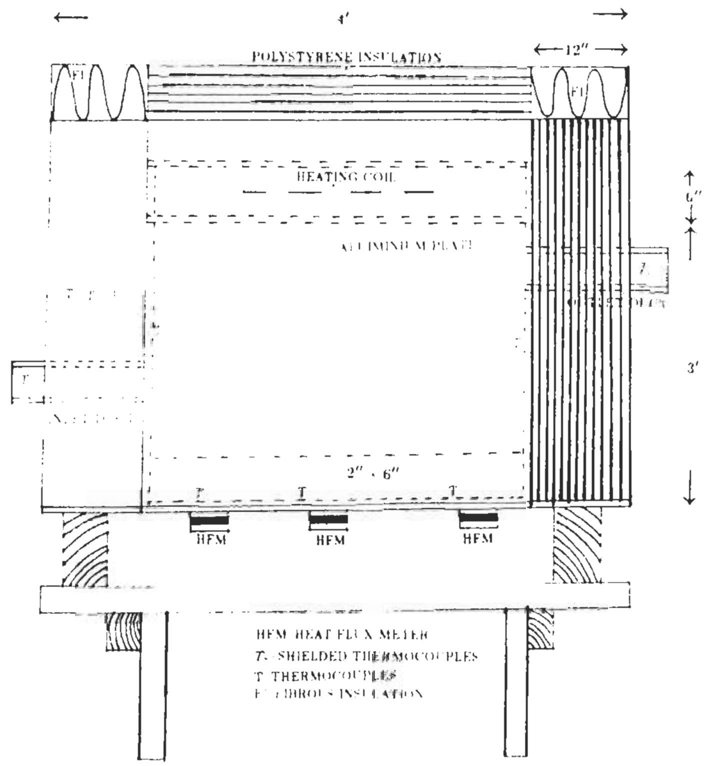

Figure. 1 Front View of The Attic Simulator

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 percent reduction in daily cooling loads for the test houses.

RADIATION EXCHANGE IN ATTICS

Radiation exchange in attics is an old concept, as it has been recognised for many years as a significant mode of heat transfer in the attic energy balance. Burch at the National Bureau of Standards (NBS), has several papers on attic heat transfer from experimental studies [5,12-14]. Headrick and Jordan [15] and Kusada, Pierce and Bean [16] have used both analog and digital methods to predict attic heat transfer. All these studies, however, treat the radiation heat transfer as a surface phenomenon, and do not account for penetration into the insulation materials itself. Joy [17] used a highly reflective aluminum foil on top of fibrous insulation in a ceiling and found that the thermal resistance of the insulation 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 be significant enough to produce an effective R-value appreciably lower than the measured value in the gaurded hot plate rating test [4]. Their studies indicated that natural convection to the attic insulation may account for as little as 10 percent of the total heat transfer through the insulation when the roof is sunlit. The Florida Solar Energy center's study had several shortcomings. The experiments were conducted within a very small box, perhaps too small to study the problem adequately. It 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.

EXPERIMENTAL SET-UP AND PROCEDURE

Figures 1 and 2 show two different views of the attic simulator. A 4 ′ × 4 ′ × 3 ′ box, with aluminum foil covering the inside walls, was constructed from 0.75 inch plywood. Two 2 ″ × 6 ″ boards were installed on the 0.5 inch sheetrock floor (ceiling) and were secured to the 0.75 inch plywood to simulate the bottom surface of an attic. The side insulation consists of multiple layers of expanded polystyrene 1 ″ board stock insulation with total total R-value of 47 on the four sides and top of the simulator.

Four fluxmeters were installed on the bottom surface to measure the ceiling heat flux. The flux meters were constructed of $3/8^{th}$ inch bakelite sandwiched between two $3/8^{th}$ inch thick aluminum plates of 6 ″ × 6 ″. Thermocouples were placed between the bakelite and both aluminum plates. By measuring the temperature drop across the bakelite the heat flux can be computed, since the thermal conductivity of the bakelite was known.

A 4 ′ × 4 ′ × 1/4″ 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 ′ × 4 ′ × 6 ″ chamber just above the aluminum plate. The aluminum plate can be maintained at a constant temperature with an aid of temperature controller. Thermocouples were placed at various places inside the box to perform the energy balance on the simulator.

DATA ACQUISITION

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

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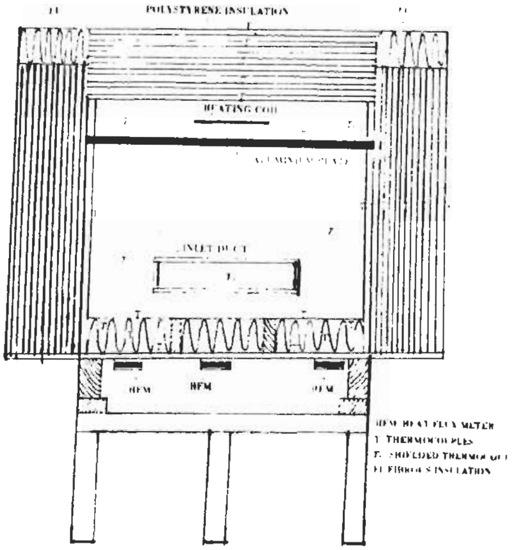

Figure. 2 Sectional Side View of The Attic Simulator

MATERIALS

An aluminum film radiation reflector was used as a radiant barrier. The cellulose insulation used was of density 2.6 lb/ft^3 (41.6 kg/m^3) with an R-value of 3.9 per inch (0.27 per cm). Fibrous insulation was of density 0.75 lb/ft^3 (12.0 kg/m^3) and R-value of 3.1 per inch (0.23 per cm).

EXPERIMENTAL RESULTS

In order 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. Calculations were performed for insulation thicknesses between 1 inch (2.54cm) and 6 inches (15.24cm) and roof deck temperatures between 145^oF (62.8^{o}C) and 100^{o}F (37.8^{o}C). The insulation systems tested were:

. Cellulose insulation (1.0″ – 2.0″)
. Fibrous insulation (1.0″ – 6.0″)
. Reflective foil
. Cellulose insulation with reflective foil
. Fibrous insulation with reflective foil
. Fibrous insulation with controlled ventilation.

The temperature profiles within the cellulose insulation are shown in Fig. 3. The profile is linear since the effect of radiation is not significant in the dense cellulose. Fig. 4 and 5 show the temperature profiles within the fibrous insulation of 1 inch and 3.5 inches respectively. Both figures show the profiles to be somewhat non-linear. The non-linearity is due to the influence of the infrared radiation at upper surface on the insulation properties of the fibrous insulation. Fig. 6 shows the temperature profile within 1 inch (2.54cm) and 3.5 inches (8.89 cm) of fibrous insulation at roof temperatures of 127^{o}F (52.8^{o}C) and 140^{o}F (60^{o}C). It is evident from Fig. 6 that for the same roof temperature and different insulation thicknesses the non-linearity increases with both the thickness of the insulation, and increasing roof temperatures. To highlight the non-linearity of the profile, the difference between calculated temperature T and the temperature for a linear profile T_{Lin} is plotted versus the thickness of the sample in Fig. 7.

The total heat flux through samples of thickness 1.0 inch (2.54cm) and 2.0 inches (5.08cm) for cellulose insulation are plotted versus the hot-plate temperatures in Fig. 8. The resistance to heat flux of 2 inches (5.08cm) of cellulose insulation with reflective foil is 50 percent greater than that of the 2 inch (5.08cm) thick cellulose insulation without reflective foil. Fig. 9 shows total heat flux through 1 inch (2.54cm) and 3.5 inch (8.89cm) fibrous insulation samples plotted versus the hot-plate temperatures. In this case also the resistance of 3.5 inch (8.89cm) thick fibrous insulation with a radiant barrier is significantly greater than the 3.5 inch thick fibrous insulation alone. A comparison of heat fluxes through 1 inch cellulose insulation with 1 inch fibrous insulation shows that they are almost equal, although low density fibrous insulation is effected by radiation. At lower insulation thicknesses the effects of radiation are not so apparent. Fig. 10 shows the temperature profile within 3.5 inches (8.89cm) of fibrous insulation with reflective foil vs the roof temperature. Because of the radiant shield the radiation effect is not significant on the hot surface of the insulation. Fig. 11 shows the heat flux through different insulation systems with reflective foil vs the roof temperature. It can be seen from Fig. 11 that the heat flux for the aluminum foil placed at the bottom of the attic floor without insulation is higher than that of the aluminum foil placed on the top of the floor joists. When the foil is placed on the floor, the joists are exposed to radiation from the roof and walls and hence, the heat flux increases. Therefore the positioning of the aluminum foil is important, since the radiation from the walls and the roof on the insulation and joists will increase or decrease depending on the position of the radiant barrier.

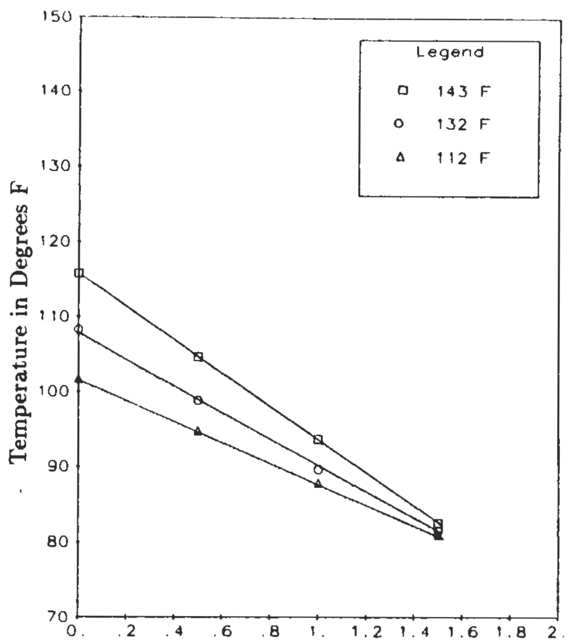

Figure. 3 Temperature Profile Within 2 Inch Cellulose Insulation System at Different Roof Temperatures.

Note: Indicated temperature is that of the roof.

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Comparisons of the temperature profiles for 3.5 inch (8.89cm) fibrous insulation with and without ventilation are shown in Fig. 12 for 127°F (52.8°C) and 111°F (43.89°C) roof temperatures, using a ventilation rate of 8 cfm (0.5 cfm/ft^2). Ventilation lowers the temperatures slightly but does not have any significant effect on the temperature profile within the insulation. Fig. 13 shows the comparisons heat flux for of 3.5 inch fibrous insulation with reflective foil and 3.5 inch fibrous insulation with and without ventilation. The change in the heat flux at 127°F and 111°F roof temperature for 3.5 inch fibrous insulation with ventilation as compared to non-ventilation is about 15 percent.

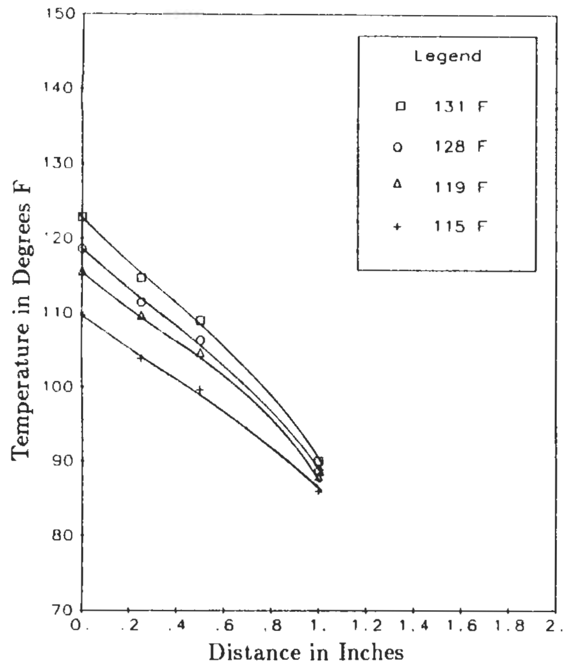

Figure. 4 Temperature Profile Within 1 Inch Fibrous Insulation System at Different Roof Temperatures.

CONCLUSIONS

One of the important conclusions drawn from this experimental study is the effect of infrared radiation on the insulation properties of fibrous materials. Experimental results showed that the temperature gradient within the fiber bed is non-linear. Also the apparent thermal conductivity was found to be much higher than that quoted by the manufacturer. There is no radiation effect on the cellulose insulation because the density of the cellulose is much higher than fibrous insulation. Thus it can be concluded that the non-linearity of the temperature profile is dependent on the thickness, temperature of the roof surface and also the density of the insulating material.

It was also found that the use of a radiant barrier such as polished aluminum foil can reduce the effect of infrared radiation on the insulation properties considerably,and thereby increase the effective thermal resistance of the whole system. The temperature profiles of the insulation systems with reflective foil were linear at the top surface of the insulation.

Ventilation, of the air space reduced the temperatures slightly but had little effect on the temperature profile within the insulation. The reduction in heat flux was also not significant.

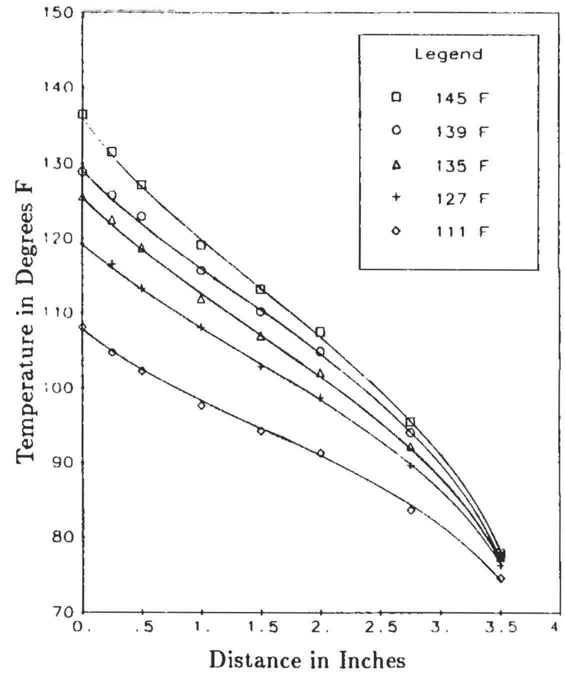

Figure. 5 Temperature Profile Within 3.5 Inches Fibrous Insulation System at Different Roof Temperatures.

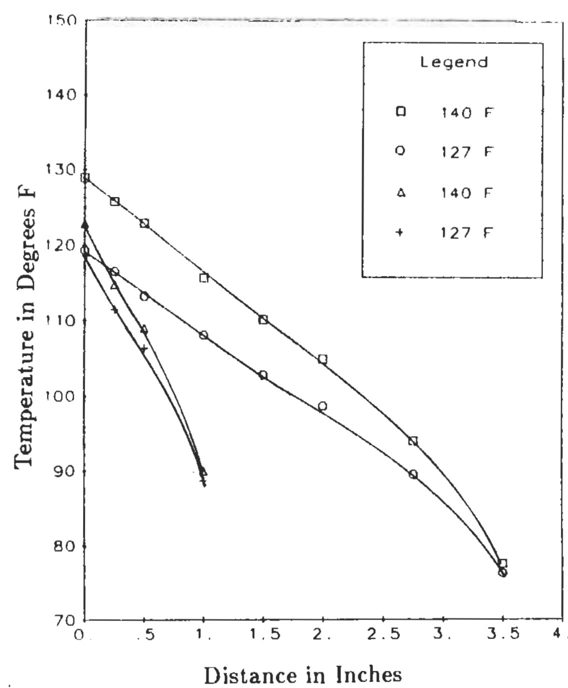

Figure. 6 Comparisons of Temperature Profiles For 1 Inch and 3.5 Inches Fibrous Insulation System at Different Roof Temperatures.

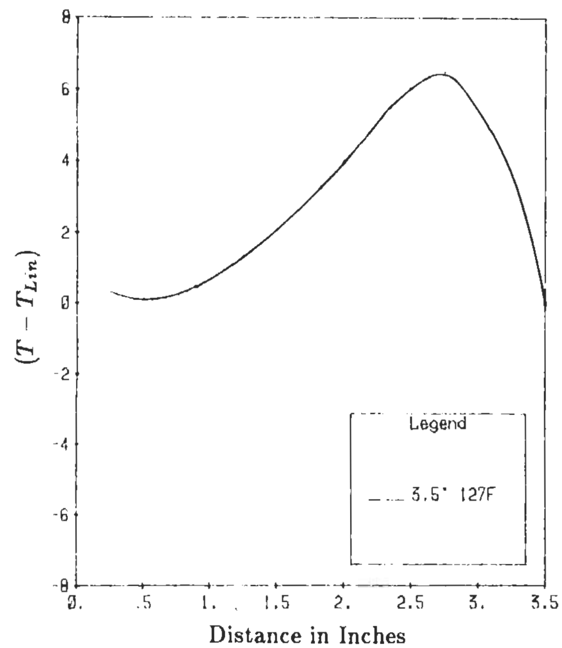

Figure. 7 Non-Linearity of Temperature Profile Within 3.5 Inches Fibrous Insulation System.

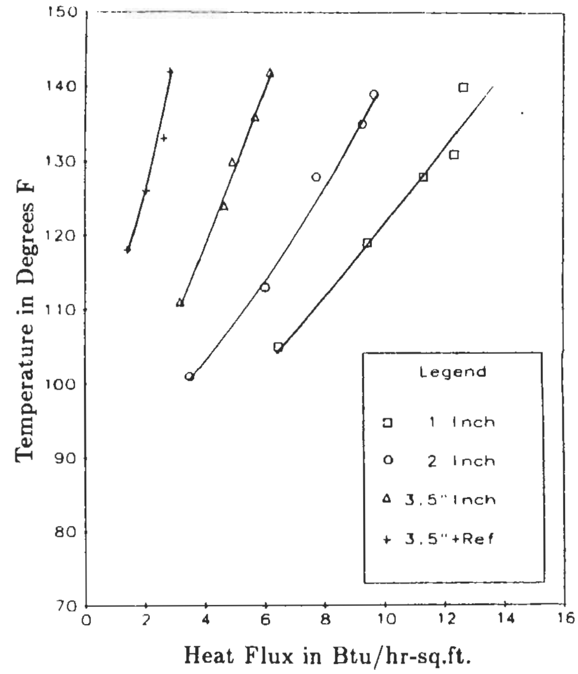

Figure. 9 Heat Flux vs Roof Temperature For Fibrous Insulation System.

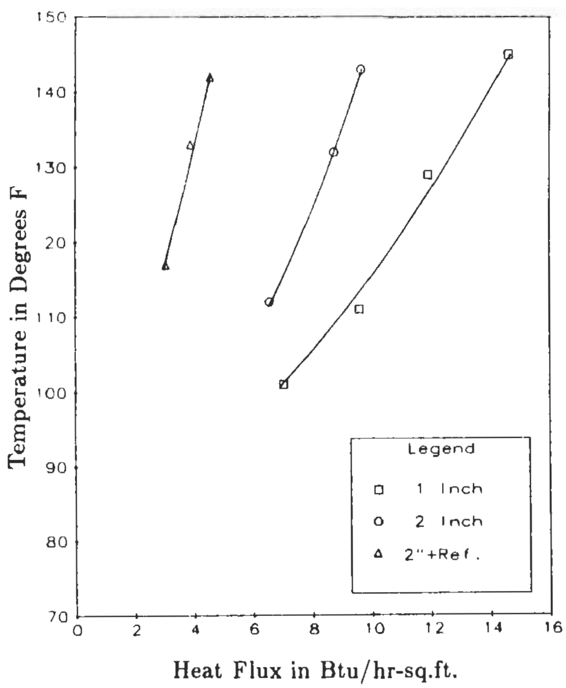

Figure. 8 Heat Flux vs Roof Temperature For Cellulose Insulation System.

Ref.:Reflective foil.

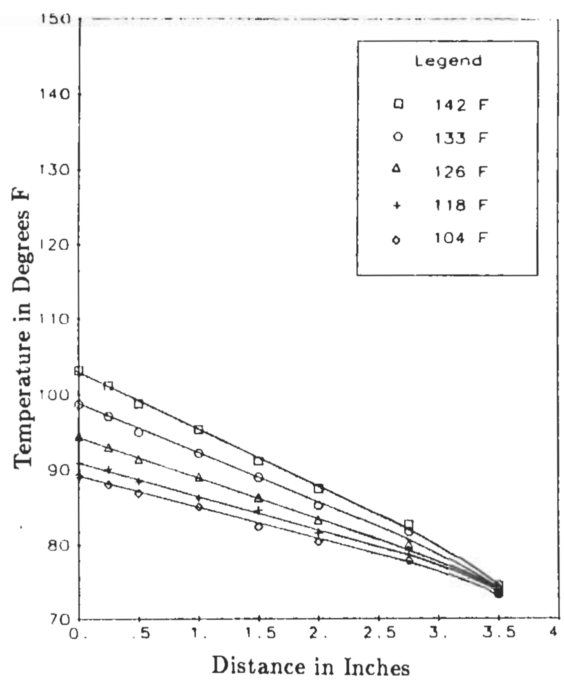

Figure. 10 Temperature Profile Within 3.5 Inches Fibrous Insulation With Reflective Foil Different Roof Temperatures.

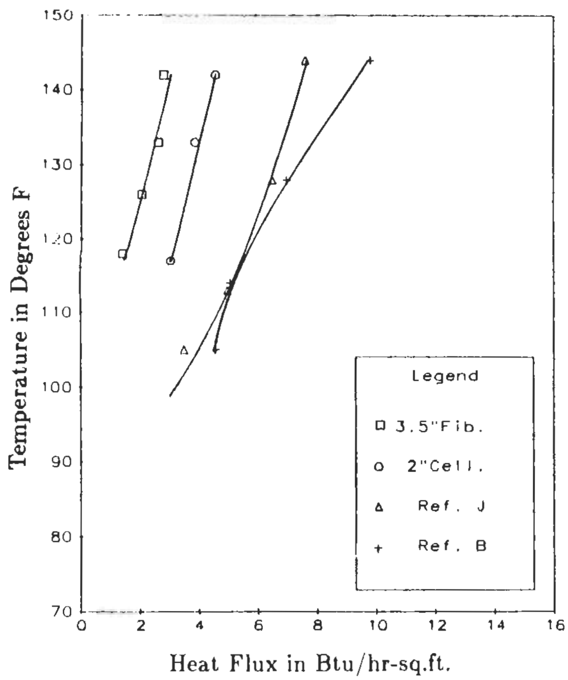

Figure. 11 Heat Flux vs Roof Temperature For Different Types of Insulation System With Reflective Foil.

J:On the Joist

B:On the Floor (Ceiling)

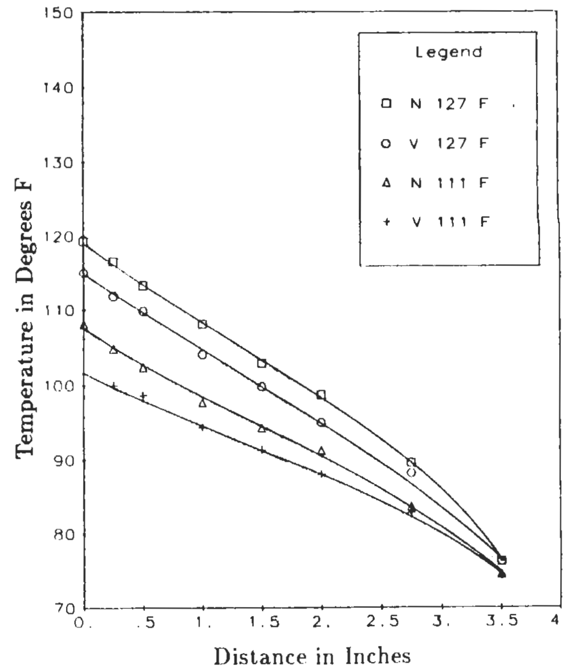

Figure. 12 Comparisons of Temperature Profiles For 3.5 Inches Fibrous Insulation System With And Without Ventilation at Different Roof Temperatures.

V:Ventilation (8 cfm) N:Non-Ventilation

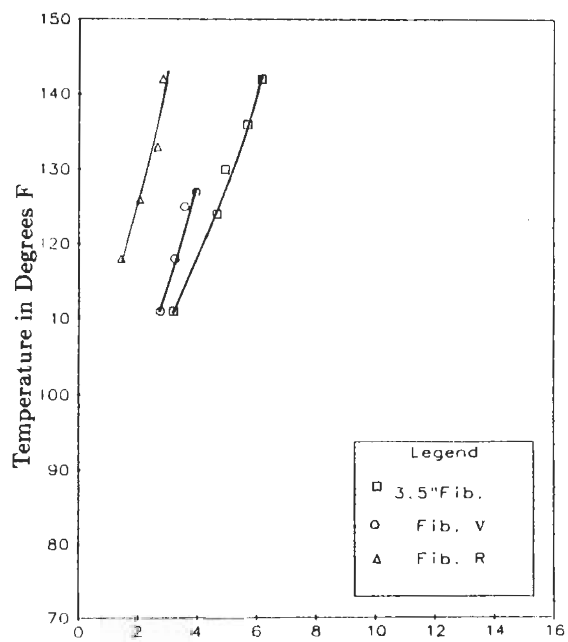

Figure. 13 Comparisons of Temperature Profiles For 3.5 Inches Fibrous Insulation With and Without Ventilation And With Reflective Foil Different Roof Temperatures.

V:Ventilation (8 cfm) R:Reflective

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