Convection in Loose-Fill Attic Insulation—Measurements and Numerical Simulations

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ABSTRACT

The objective of this study is to investigate the influence of convection on the thermal performance of loose-fill attic insulation under realistic climatic conditions. Measurements have been performed in a large-scale attic test model to determine heat transfer through the attic floor due to convection. Natural convection occurs in low-density materials only, leading to an increase in heat flow through the insulation and, thus, to a decrease in the thermal resistance of the insulation. The measurements show that the critical modified Rayleigh number for the low-density attic insulation in the studied setup is 22 to 25. At a modified Rayleigh number of 34, the thermal resistance of the insulation in the attic test model is only 75% of the highest measured thermal resistance.

INTRODUCTION

In Sweden, approximately 40% of the total energy use is related to buildings, and 70% to 90% of this energy is consumed during the occupation phase of the building (Adalberth 2000). Consequently, well-insulated building components are beneficial both to the environment and to the individual homeowner. Sweden has one of the highest degrees of insulation in the world, with an average attic insulation thickness of 0.5 m and an average wall insulation thickness of 0.3 m (Energimagasinet 2000). Thicker insulation is usually more difficult to apply than thin insulation and, furthermore, the consequence of an imperfection in a thick insulation will have a greater impact on the final thermal resistance of the insulation. Loose-fill insulation is commonly used in residential buildings, in particular, in attic floors. The main advantage of loose-fill insulation compared to insulation boards is that the installation procedure is easy, fast, and there is little waste. However, loose-fill insulation has a high air permeability, which allows air movement—convection—in the insulation. Natural convection is caused by density differences between cold and warm air. There is greater risk of natural convection in thick insulation and in cold climates. Attic insulation is also affected by air movement in the attic space—forced convection. In a typical Swedish attic, the ventilation air enters the attic at the eaves, passes over a wind protection, and then flows into the attic space (see Figure 1).

There are several consequences of convection in insulation. Primarily, air movement causes extra heat loss through the insulation, resulting in higher energy costs and poor thermal comfort in the building. Convection can also influence

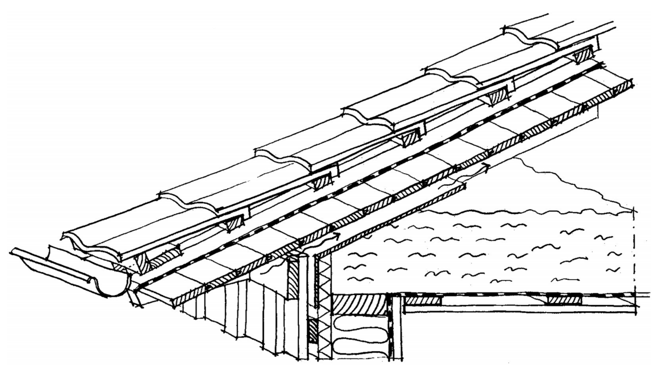

Figure 1 *Ventilation inlet for an attic with loose-fill insulation.*

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moisture distribution in the attic. This can lead to high moisture conditions and, as a result, mold and deterioration.

In this study, a Swedish attic is investigated under the influence of the Scandinavian winter climate. Large-scale measurements were performed, and the measurements were compared to three-dimensional numerical simulations. The aim is to estimate the influence of natural and forced convection on attic insulation and to validate the numerical model against measurements. The numerical model will, in the future, be used for further studies, such as of the influence of workmanship, different attic ventilation strategies, or of the annual effect of convection with respect to non-steady-state conditions.

The influence of natural and forced convection on the thermal performance of loose-fill insulation has been investigated in both small-scale and large-scale experiments, as well as with numerical simulation models. Convection in attic insulation is not only dependent on the material properties of the insulation and on boundary conditions, such as temperatures and air velocities, but also on the thickness of the material and on the geometry of the insulation. Thermal bridges, such as joists, and inhomogeneities in the insulation also affect convection. Therefore, it is important to study attic insulation in large-scale equipment under realistic climatic conditions. Large-scale measurements of the thermal resistance of attic insulation have been performed by Anderlind (1992), Löfström and Johansson (1992), Rose and McCaa (1991), Wilkes and Rucker (1983), and Wilkes et al. (1991). Anderlind (1992) and Löfström and Johansson (1992) have made measurements at low modified Rayleigh numbers and have found no significant effect of natural convection on the thermal resistance of attic insulation. The other investigations included measurements of more permeable materials that were affected by natural convection. Wilkes et al. (1991) have measured thermal resistances that were a factor of two lower than the estimated nominal thermal resistance of the insulation. Large-scale measurements of attic ventilation by Wilkes et al. (1991), Rose and McCaa (1991), and Anderlind (1992) have shown no decrease in the thermal resistance of the attic floor due to attic ventilation.

The influence of joists in the insulation has been studied both numerically and experimentally by Delmas and Wilkes (1992) and Wahlgren et al. (2001) and numerically by Delmas and Arquis (1995). These authors have concluded that introducing a joist into the insulation can decrease the critical modified Rayleigh number and also that the joist can be an obstacle to motion at high modified Rayleigh numbers. The effect of the joist depends on the thermal conductivity ratio between the joist and the insulation and also on the size of the joist and on the distance between joists (see Delmas and Arquis [1995]).The thermal resistance measurements presented in this paper have been performed in a large-scale attic test model. The measurements of natural convection have been compared to numerical simulations and show good agreement.

METHOD

The methodology is to measure the influence of convection and to compare the measurements to numerical simulations. The strengths and limitations of the simulation program are investigated so that the program, in the future, can be used to study the influence of various factors on convection, such as workmanship, attic ventilation strategies, non-steady-state climatic conditions, and moisture. The measurements were performed in a large-scale attic test model under winter conditions (see Figure 2). Tests were run both with and without attic ventilation (forced and natural convection).

Rockwool boards were initially used in the attic floor to calibrate the attic test model. Thereafter, tests were performed on two different loose-fill materials—rockwool insulation and fiberglass insulation with a low density. Only measurements on low-density, fiberglass insulation without attic ventilation are presented in this paper.

The thermal resistance of one square meter of attic floor with insulation was determined by measuring heat flow through the attic floor, Q_{box}, and the surface temperatures on the warm side and cold side of the attic floor, which gives the temperature difference across the attic floor, $\Delta T_{attic\ floor}$. A metering box with an area, A_{box}, of 1.0 m^2 (11 ft^3) has been used to estimate heat flow (see Figure 3).

The thermal resistance, m^{2}K/W (ft^2·h·°/Btu), is calculated according to

$$R_{measured} = \frac{\Delta T_{attic\ floor}}{Q_{box}} \cdot A_{box}\ . \qquad (1)$$

The thermal resistance is presented as a function of the modified Rayleigh number, which, in turn, is a function of the properties of the air in the insulation, the properties of the insulation material, temperatures, and insulation thickness. The modified Rayleigh number, Ra_m, is calculated as follows (Nield and Bejan 1999):

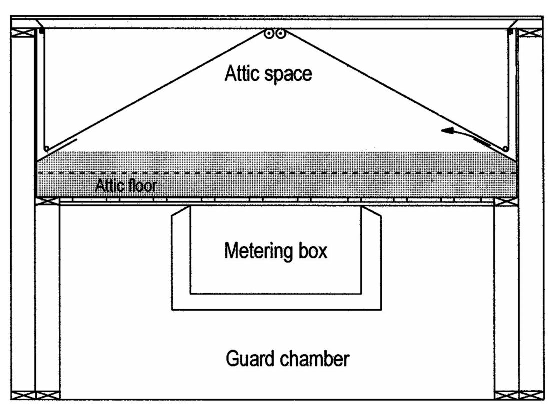

Figure 2 *The attic test model; width 3.3 m (20 ft), length 6.1 m (11 ft), and height 2.3 m (7.5 ft).*

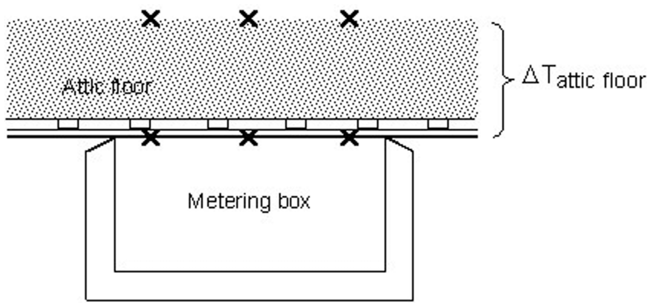

Figure 3 *Thermocouple locations at the upper and lower surfaces of the attic floor that give the temperature difference across the attic floor,* $\Delta T_{\text{attic floor}}$.

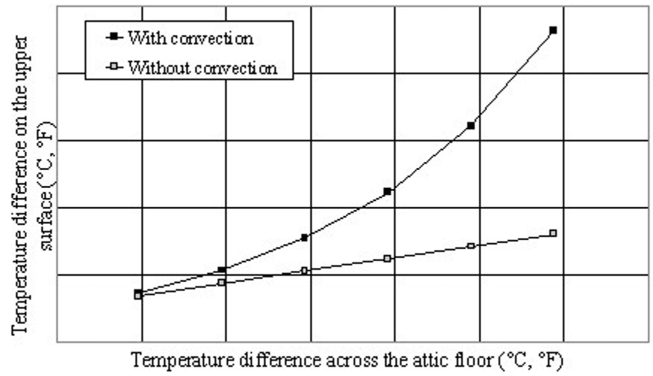

Figure 4 *Simulated temperature difference on the upper surface of insulation with joists.*

$$Ra_m = \frac{g\beta\rho c_p}{\upsilon} \cdot \frac{dk\Delta T}{\lambda} \tag{2}$$

The properties of the air are the heat expansion coefficient β, kinematic viscosity υ, density ρ, and specific heat capacity c_p. The insulation material properties are air permeability k, thermal conductivity (without convection) λ, and thickness d. The temperature difference across the material is ΔT and acceleration due to gravity is g.

When the modified Rayleigh number exceeds a certain value, the critical modified Rayleigh number, $Ra_{m,cr}$, convection starts in the insulation and adds to the total heat flow through the insulation. This results in a decrease in the thermal resistance of the attic floor. The magnitude of the critical modified Rayleigh number depends on the geometry of the material and on boundary conditions. In an attic, the critical modified Rayleigh number of the insulation is also affected by thermal bridges, such as joists and gables.

The surface temperatures on the upper surface were studied to detect air movement (convection cells) in the insulation. Air movement causes a nonlinear temperature variation on the upper surface when plotting the temperature difference on the upper surface as a function of temperature difference across the attic floor. When there is no air movement in the insulation (solely conduction) there will be a linear increase in temperature difference. This increase is caused by the joist in the insulation, which acts as a thermal bridge. The temperature difference on the upper surface is, in the following text, defined as the temperature difference between the warmest and the coldest measured (or simulated) temperature on the upper surface. The described effect is illustrated in Figure 4, in which the two-dimensional numerical model CHConP (Serkitjis and Hagentoft [1998]) has been used to simulate insulation with a joist.

The thermal resistance measurements were compared with simulations made with a commercial three-dimensional computational fluid dynamics (CFD) program. The CFD simulations have been compared to analytical solutions of natural and forced convection, showing good agreement. In the case of natural convection, a horizontal porous layer, bounded on the upper and lower surfaces by isothermal and impermeable boundaries, was investigated. Forced convection was investigated for an insulation layer that is open on one side and impermeable on the other. There is an open slit in the impermeable surface in which air infiltrates the insulation under the influence of a pressure gradient and then leaves through the open surface (see Claesson [1993] and Mattsson [2004]).

The program is used to calculate heat flows, airflows, and temperatures in and through the attic floor with natural and forced convection but without moisture flow and latent heat transfer.

MEASUREMENT EQUIPMENT

The attic test model has a large attic area, 18 m² (194 ft²), and is constructed in a climate chamber. The attic floor is divided into two halves: a homogeneous area for calibration, where the insulation lies on a floor of particle boards overlayed with plastic foil, and a conventional attic floor. The conventional attic floor is constructed to simulate a typical Swedish attic floor and consists of joists (145 × 45 mm, c/c 1200 mm, [0.15 × 0.48 ft, c/c 3.9 ft]) in the insulation, with a ceiling of gypsum board (13 mm [0.043 ft]), secondary spaced boarding (70 × 28 mm, c/c 300 mm [0.23 × 0.092 ft, c/c 0.98 ft]), and a vapor barrier (0.2 mm [$8 \cdot 10^{-3}$ in.]) (see Figure 5). Measurements presented in this paper are performed in the conventional attic part.

Given that the objective is to study attic insulation under normal winter conditions, the guard area is constantly warm, representing indoor climate, and the attic space is cold, representing Swedish winter climate. Keeping the warm side at a constant level causes a decrease in mean temperature in the attic insulation when the attic space temperature decreases. Since the thermal conductivity of the insulation material

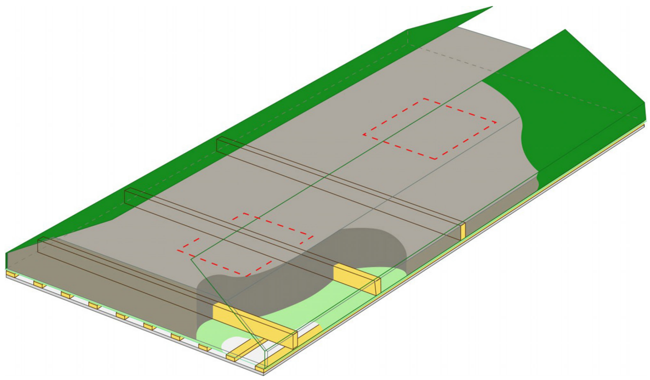

Figure 5 *The attic floor in the attic test model when wind protection and loose-fill insulation are applied. The dotted squares show the two locations of the metering box in contact with the ceiling.*

depends on the mean temperature of the material, this relationship has to be known in order to separate the effect of convection on the thermal resistance of the insulation. The studied loose-fill fiberglass has a thermal conductivity according to

$$\lambda = 0.000377 \cdot T_{mean} + 0.0483 \text{ W/m} \cdot \text{K} \qquad T_{mean} = \frac{T_{warm} + T_{cold}}{2} \text{ in °C}$$
$$\left(\lambda = 0.00145 \cdot T'_{mean} + 0.288 \text{ Btu} \cdot \text{in./h} \cdot \text{ft}^2 \cdot \text{°F} \qquad T'_{mean} = \frac{T_{warm} + T_{cold}}{2} \text{ in °F}\right). \tag{3}$$

Attic floor surface temperatures were measured with thermocouples (see Figure 3) on the upper, cold surface (at nine locations) and lower, warm surface (at six to nine locations) to detect convection cells, as previously described, and to calculate the thermal resistance of the attic floor, as described in Equation 1.

The low-density, loose-fill fiberglass insulation that is used for the measurements described in this paper is not normally used in buildings in Sweden. A typical Swedish loose-fill fiberglass insulation for attic floors has a density of approximately 20 kg/m^3 (1.2 lb/ft^3). The low-density, loose-fill fiberglass insulation is only included in the investigation to study convection at high modified Rayleigh numbers. The fiberglass insulation was tested at a thickness of 0.44 m (1.4 ft), its density was 9.4 kg/m^3 (0.59 lb/ft^3), and its air permeability was $4 \cdot 10^{-8}$ m^2 ($4 \cdot 10^{-7}$ ft^2). More information about the attic test model can be found in Wahlgren (2002).

Error Analysis of the Measurements

A simple error analysis has been made of the modified Rayleigh number and of the measured thermal resistance. The error analysis was based on the following formula, which states that the maximum error is the sum of the relative error of each variable:

$$\Delta F = \left| \sum_{k=1}^{n} \frac{\partial F}{\partial x_k} \Delta x_k \right| \tag{4}$$

Using Equation 1 for the modified Rayleigh number results in a maximum relative error of

$$\frac{\Delta Ra_m}{\Delta Ra_m} = \left|\frac{\Delta d}{d}\right| + \left|\frac{\Delta k}{k}\right| + \left|\frac{\Delta(\Delta T)}{\Delta T}\right| + \left|\frac{\Delta\lambda}{\lambda}\right|. \tag{5}$$

The term that contributes the most to the maximum relative error is permeability. It was measured according to the Swedish standard SS 02 15 50, "Thermal Insulation—Porous Insulation Materials—Determination of Permeability." However, there are some problems in accurately measuring the permeability of highly permeable materials, since the applied pressure difference is small. Increasing the pressure difference is difficult because this results in an increase in airflow through the material. As a result of the increase in airflow, turbulence can develop in the material and a redistribution of the material can take place. The described test procedure was, however, modified for loose-fill insulation by increasing the thickness of the test material, thus allowing a higher pressure difference to be applied. Standard permeability measurements have a maximum error of 5%, according to SP Swedish National Testing and Research Institute, who performed the measurements. The largest maximum relative error in the modified Rayleigh number for the setup with fiberglass insulation is 9%. An error in the measured permeability mainly affects the modified Rayleigh number of the measurements and not of the simulations. The thermal resistance of simulations as a function of the modified Rayleigh number is unique for each setup and does not vary significantly with permeability.

The maximum error in measured thermal resistance is calculated similar to the error in the modified Rayleigh number. Using Equation 4 on Equation 1 results in

$$\frac{\Delta R}{R} = \left|\frac{2\Delta l}{l}\right| + \left|\frac{\Delta(\Delta T_{attic\ floor})}{\Delta T_{attic\ floor}}\right| + \left|\frac{\Delta Q_{box}}{Q_{box}}\right|, \tag{6}$$

where l (m [ft]) is $\sqrt{A_{box}}$.

The error in measured thermal resistance depends on the measuring situation and is strongly dependent on the error in heat input to the box. The maximum relative error in thermal resistance for the setup with fiberglass insulation is approximately 8%. Details on the error analysis can be found in Wahlgren (2001).

SIMULATIONS

The two-dimensional simulation program, CHConP, was initially used to investigate the influence of the secondary spaced boarding in the ceiling. The boarding causes a non-isothermal lower surface, which might affect the onset of convection. The conclusion from these simulations is that the secondary spaced boarding can be represented in the model by a board with a specific thermal resistance.

Table 1. Summary of the Conclusions Drawn from Surface Temperature Measurements

Material	Temperature Difference across the Attic Floor °C	°F	Indications of Air Movements
Rockwool, without joists	25-44	45-79	Yes
Rockwool, with joists	32-47	58-85	Yes, minor
Fiberglass, with joists	20-32	36-58	Yes

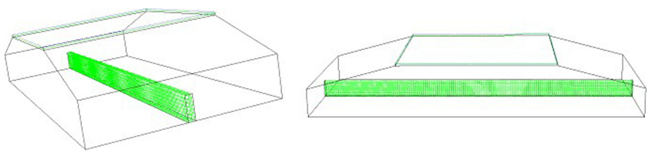

Figure 6 *The simulation setup used in the CFD simulations, showing the geometry of the studied fiberglass loose-fill insulation with an open upper surface, a joist in the insulation layer, and adjacent wind protection boards.*

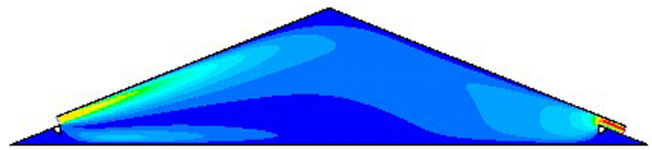

Figure 7 *An example of velocity magnitudes in the attic space. The inlet velocity is 0.1 m/s (0.3 ft/s) from the right.*

Natural convection in the attic insulation was simulated with a three-dimensional CFD program. The simulated setup is shown in Figure 6. A width of 1.2 m is studied, since this is the distance between the joists. The simulation is made with an open upper insulation surface, having a thermal resistance of 0.2 m^2K/W (1.1 $ft^2{\cdot}h{\cdot}°F/Btu$), as suggested by Serkitjis (1995).

Three-dimensional CFD simulations of forced convection were performed to investigate the influence of airflow (ventilation) in the attic space on the thermal performance of the attic insulation. The idea of this preliminary study is to separate the attic space from the attic insulation in order to simplify the simulations. Some simulation difficulties are encountered when the relatively high air velocities in the attic space are calculated simultaneously with the lower velocities in the porous insulation. Furthermore, it can also be troublesome to combine, for example, the small air inlet in the attic space and the large insulation volume, with regard to convergence and meshing. Therefore, forced convection in the attic space is simulated independently of the attic insulation. The simulations of air movements in the attic space are two-dimensional with air entering the attic space at the eaves on one side and exiting on the other. The simulations of the air in the attic space were performed by Arild Gustavsen at NTNU, Norwegian University of Science and Technology, for different inlet velocities. An example is shown in Figure 7.

The pressure obtained on the lower surface of the attic space is transformed into discrete pressures at steps of 0.002 m, which is applied to the upper surface of the geometry shown in Figure 6. The comparison between measurements and simulations shows that there is poor agreement between the two. Consequently, the comparison demonstrates that the simplifications that were made for the simulations are not suitable for this setup. The interaction between the attic space and the insulation need to be accounted for and, as a result, new simulations are required that treat the attic space and the attic insulation a whole.

COMPARISON BETWEEN MEASUREMENTS AND SIMULATIONS

In the following, only the results from the loose-fill fiberglass insulation, without attic ventilation, in the conventional attic part are presented. However, the measurement results from thermal resistance and surface temperature investigations of rockwool loose-fill insulation are included in Table 1. All measurement results are found in Wahlgren (2001).

Surface Temperatures

The fiberglass loose-fill insulation has a high permeability, so a measured modified Rayleigh number of 34 is reached within the metering area. At modified Rayleigh numbers this high, the joist causes an upward airflow in the insulation material in the vicinity of the joist. This warm air has been detected in the surface temperature measurements and in CFD simulations. The thermocouple locations are shown in Figure 8a, where eight thermocouples are placed at the perimeter of the upper metering surface and one at the center. An example of the temperatures measured on the fiberglass surface is shown in Figure 8b. A similar profile is obtained when the corresponding setup is simulated with the CFD program. Figure 8c shows the simulated temperature profile of the open upper surface of the attic floor at the same modified Rayleigh number.

The measured temperature difference of the upper surface increases strongly with an increase in temperature difference across the attic floor and, consequently, with an increase in the modified Rayleigh number, as shown in Figure 9. This indi-

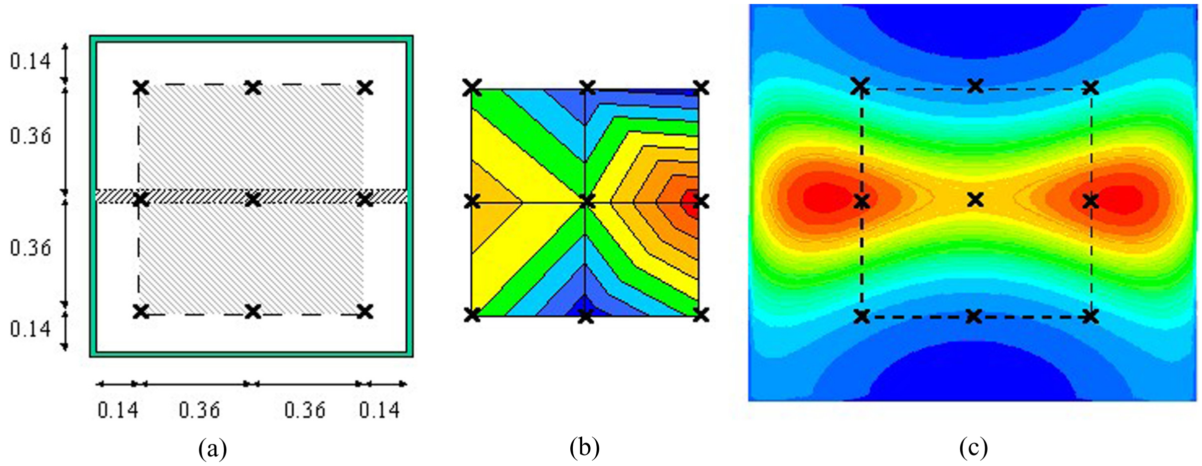

Figure 8 *(a) Thermocouple location, X, joist, and displayed area in Figure 8b. (b) Measured temperature profile on the upper surface of fiberglass insulation. Displayed area 0.72 × 0.72 m (2.4 × 2.4 ft). The temperature difference on the surface is 4.4°C (39.4°F) and it is measured at a modified Rayleigh number of 34. (c) Simulated temperature profile of the upper surface of fiberglass insulation. The displayed area is 1.2 × 1.4 m (3.9 × 4.6 ft). The dotted square measures an area of 0.72 × 0.72 m (2.4 × 2.4 ft), which corresponds to the area shown in Figure 8b. The temperature difference within the dotted square is 3.6°C (38.5°F), and the modified Rayleigh number is 34.*

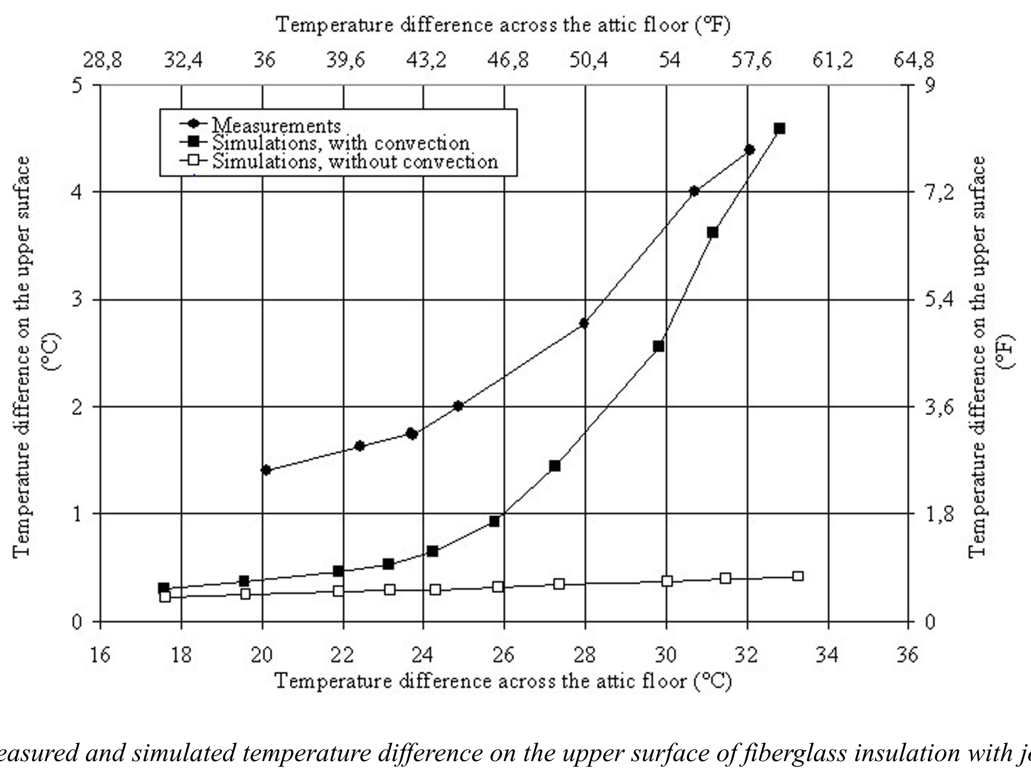

Figure 9 *Measured and simulated temperature difference on the upper surface of fiberglass insulation with joists.*

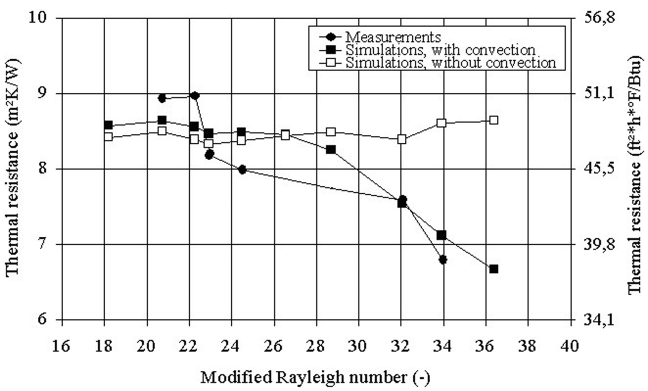

Figure 10 *Thermal resistance of the attic floor with joists and fiberglass insulation.*

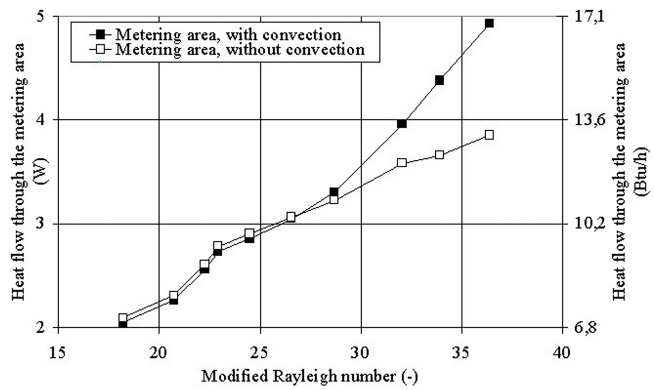

Figure 11 *Simulated heat flow through the metering area.*

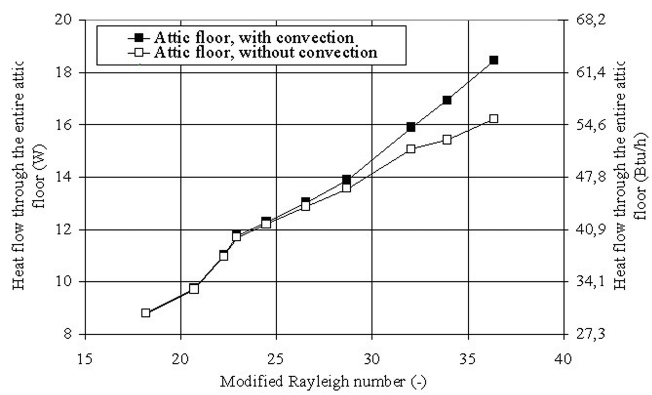

Figure 12 *Simulated heat flow through the entire attic floor.*

cates that natural convection occurs in the insulation, which is further verified in the study of thermal resistance. There seems to be a breaking point in the measurements at a temperature difference across the attic floor of approximately 24°C (43°F). This corresponds to a modified Rayleigh number of 24-25. The simulations with convection have a gradually increasing gradient in Figure 9, from which it is difficult to estimate a critical modified Rayleigh number.

Thermal Resistance

The thermal performance of the fiberglass insulation is strongly affected by natural convection (see Figure 10). A comparison of the highest measured thermal resistance, at a modified Rayleigh number of 22, and the measured thermal resistance at the maximum modified Rayleigh number, 34, shows a decrease in thermal resistance of approximately 25%. The temperature differences across the attic floor for these two cases are 22°C and 32°C (40°F and 58°F), respectively. The measurements display a drastic decrease in thermal resistance at a modified Rayleigh number between 22 and 23, which indicates that the critical modified Rayleigh number is in this region. The simulations, however, have a slightly higher critical modified Rayleigh number, between 24.5 and 26.6. All simulated thermal resistances correspond to a measurement situation, except the highest and lowest modified Rayleigh numbers and the simulated thermal resistance at a modified Rayleigh number of 26.6. This modified Rayleigh number was only simulated to detect the onset of convection.

Comparing the three-dimensional simulations of the attic floor with convection and without convection shows that there is some air movement even at low modified Rayleigh numbers. When there is convection in the simulations, the temperature difference across the boarding, on which the insulation is placed, is slightly lower within the metering area than in the case without convection. A smaller temperature difference causes lower heat flow through the metering area and, consequently, a higher thermal resistance for the attic floor within the metering area. The heat flow through the metering area is shown in Figure 11 and the heat flow through the entire attic floor is shown in Figure 12. Here, there is initially very little difference between the simulations with and without convection for the entire attic floor. The difference increases with increasing modified Rayleigh number, and there is no clear critical modified Rayleigh number. The simulated heat flows within the metering area indicate that the onset of convection occurs at modified Rayleigh numbers between 24.5 and 26.6.

SUMMARY OF THE RESULTS OF NATURAL CONVECTION IN LOOSE-FILL INSULATIONS

The thermal performance of rockwool and fiberglass loose-fill insulation in an attic floor has been investigated. Measurements have been performed in a large-scale attic test model under realistic climatic conditions. In this paper, the results of natural convection in fiberglass insulation have been compared to three-dimensional CFD simulations.

Table 2. Summary of the Effect of Air Movement on Thermal Resistance

Material	Maximum Ra_m	Influence of Air Movement in the Insulation on Thermal Performance
Rockwool, without joists	10	No
Rockwool, with joists	11	No
Fiberglass, with joists	34	Decrease

The presence of air movement within the insulation material has been indicated by surface temperature measurements. Air movement in the material causes a nonlinear increase in the temperature difference on the upper surface with an increase in temperature difference across the attic floor. Table 1 shows indications of air movement inside the insulation material based on surface temperature measurements.

Thermal resistance measurements were used to investigate the influence of air movement in the insulation within the metering area. The results are presented in Table 2 for each measurement configuration.

The estimated critical modified Rayleigh number varies slightly depending on how it is determined. When the measured surface temperatures of the loose-fill fiberglass are studied, the estimated critical modified Rayleigh number is between 24 and 25. The measurements of thermal resistance give a critical modified Rayleigh number of 22 to 23. The corresponding number for the simulations of thermal resistance is 24.5 to 26.6, which is similar to when heat flows are studied. The range for the onset of convection is, thus, 22 to 27. The decrease in thermal resistance when comparing the resistance at a modified Rayleigh number of 34 and of 22 is 25% for the measurements and 22% for the simulations. It is important, however, to remember that this is the case within the metering area. Comparing the simulated heat flow over the entire attic floor shows that heat flow with convection is only 10% higher than the heat flow without convection at a modified Rayleigh number of 34.

The critical modified Rayleigh numbers estimated here are slightly higher than those estimated by Wilkes et al. (1991), which may be due to the larger distance between the joists, 1.2 m (3.9 ft) in this study compared to 0.6 m (2.0 ft). Wilkes et al. estimate the measured critical modified Rayleigh number to be 13 to 20. The large variation is caused by an uncertainty in the permeability of the insulation material. Comparing the highest measured thermal resistance with the lowest measured thermal resistance shows a decrease of 37% within the metering area.

CONCLUSIONS

The investigations have shown that natural convection has a great impact on the thermal performance of low-density, loose-fill insulation. This study has also shown that there is good agreement between measurements and three-dimensional CFD simulations. As a result, it is possible to use the simulation program to further investigate convection in attics with loose-fill insulation.

The initial simulations on attic ventilation have demonstrated that it is necessary to simulate the attic floor with insulation and the attic space with ventilation air as a whole in order to account for the interaction between the insulation surface and air in the attic.

Results from the measurements have shown that the thermal resistance of the attic floor with fiberglass insulation, without ventilation, decreases rapidly when the modified Rayleigh number exceeds 22. This indicates that natural convection has started in the insulation. The same effect is found in the simulations but at modified Rayleigh numbers between 24.5 and 26.6. A comparison of the highest measured thermal resistance and the thermal resistance at the maximum measured modified Rayleigh number shows a decrease of approximately 25%. The corresponding decrease in the simulations is 22%.

FUTURE WORK

The continuation of this project consists primarily of further investigating attics, in particular, the effect of convection over the entire attic floor, using CFD simulations. Attic ventilation will be studied, as previously described, and simulations that take into account the interaction between porous material and cracks and voids in the insulation will be made. This situation corresponds to poor workmanship and to damage to the insulation. The attic will also be studied under non-steady-state conditions since an attic is subjected to varying boundary conditions caused by diurnal and annual variations of the outer climate.

ACKNOWLEDGMENT

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