
Convection in Loose-fill Attic Insulation—Simulations and Large-Scale Measurements

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ABSTRACT

A large-scale model of a ventilated attic has been built in a climatic chamber to investigate heat transfer in loose-fill attic insulation, in particular heat transfer by convection and its effect on heat losses through the attic floor. Initial measurements in the attic test model have been made on homogeneous, high-density, mineral wool boards to verify the performance of the attic test model without convection. Thermal resistance measurements on loose-fill insulation show that the measured and calculated thermal resistance of the attic floor is within the margin of error. Both measurements and simulations indicate air movements in the insulation, which are detectable by studying the temperature patterns at the surface of the insulation. However, the air movements are insufficient to cause a decrease in the thermal resistance of the attic floor. Attic ventilation has a minor effect on the measured thermal resistance of the attic floor but does cause a decrease in temperature at the upper surface of the insulation.

INTRODUCTION

Loose-fill insulation is commonly used in attic floors in Swedish residential buildings. The main advantage of loose-fill insulation, compared to insulation boards, is the installation procedure, which is easy and fast; the loose-fill insulation is blown into place. As a result, pipes and other installations are easily covered and there is little waste. However, the loose-fill insulation is permeable to air and has no wind protection, which makes the insulation susceptible to both natural and forced convection. Since the amount of convection in loose-fill insulation depends on the thickness of the insulation and of the geometry of the attic, measurements of convection need to be performed with large-scale equipment. This has previously been done under laboratory conditions in the USA and in Canada by, among others, Wilkes et al. (1991), Rose and McCaa (1991), Besant and Miller (1983), and Wilkes and Rucker (1983) and under natural weather conditions in Sweden by Löfström and Johansson (1992) and Anderlind (1992). The American measurements show signs of convection, which is not the case in the Swedish measurements. This is not surprising since the measurements in Sweden were

performed on loose-fill insulation with a lower permeability and a smaller temperature difference across the insulation, not representative of a Swedish winter. Loose-fill insulation with joists is modeled two-dimensionally by Delmas and Arquis (1995) and Delmas and Wilkes (1992). A review of the literature on convection in loose-fill attic insulation is found in Fryklund (1997a).

The present study investigates heat flows and air movements in common Swedish loose-fill, rockwool insulation and rockwool boards applied in a large-scale attic test model. The attic test model is placed in a climate chamber and heat flows through the attic floor are measured, along with temperatures in and on the surface of the insulation. The measurements are compared to simulations, the discrepancies are investigated and discussed, and an error analysis is presented.

ATTIC TEST MODEL

The large-scale attic test model (18 m², 194 ft²) is constructed to simulate a residential building with a ventilated attic. The attic model is located in a climate chamber, where a minimum temperature of –25°C (–13°F) can be obtained.

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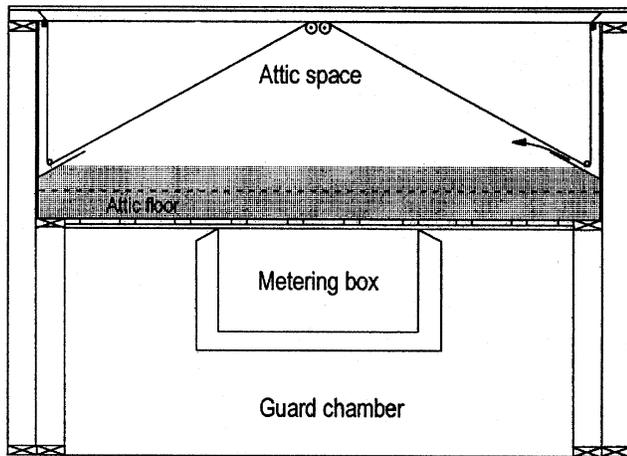


Figure 1 The four major parts of the attic model.

The model consists of four major parts: an attic space, an attic floor, a guard chamber, and a movable metering box (see Figure 1).

The attic space is not insulated against the climate chamber and has an attic ventilation system that supplies air from the climate chamber. The ventilation air enters the attic through the eaves on one side of the attic and exits through the eaves on the other side. When loose-fill insulation is tested, wind protection is mounted at the eaves, according to the manufacturer, to prevent the air from directly entering the insulation.

The attic floor consists of two halves: one homogeneous area, where the insulation lies directly on a floor of particleboards with overlaying plastic foil, and one traditionally constructed floor with gypsum board, secondary spaced boarding, plastic foil, joists, and insulation. Any type of insulation can be used in the attic and thicknesses up to one meter can be installed.

The guard chamber simulates normal indoor climate, i.e., temperatures from 20°C to 25°C (68°F to 77°F) are applied. The guard is regulated to follow the temperature of the metering box, which has a set temperature. By measuring the temperature difference over the metering box walls, the needed heat input to the guard is determined.

The metering box has an area of 1 m² (10.8 ft²) and is equipped with a heating element, four fans, and twenty thermocouple pairs in series at the walls. The metering box has been thoroughly calibrated and the thermal resistance calibration result, on polystyrene boards, was within 1% of that measured at SP, the Swedish National Testing and Research Institute. Descriptions of the metering box calibration, temperature and heat flow measurements, details of the construction of the attic test model, and the performance of the climate chamber can be found in Fryklund (1997b).

TEST PROGRAM

The test program for the attic test model is designed as follows:

1. The metering box is calibrated in a horizontal hotbox, the Wind Box, using a polystyrene board. The outcome of this calibration is described in Fryklund (1997b) and briefly in Wahlgren (1998).
2. The attic test model, including the metering box, is calibrated with high-density, rockwool boards that are used to ensure that there is no convection in the material. The calibration is made on the homogeneous part of the attic floor to avoid the influence of thermal bridges (joists). The measured thermal resistance of the ceiling agreed with the thermal resistance based on standard measured thermal conductivities. Measurements on mineral boards with attic ventilation showed a 1% increase in heat flow compared to no ventilation, which is within the accuracy of the metering equipment. Since rockwool boards have low air permeability there should be no effect of forced convection.
3. Next, a gap of 1 cm (0.4 in.) was created between two boards, halfway through the insulation. This caused an increase in heat flow in the metering area of approximately 10%, in agreement with computer simulations.
4. Finally, loose-fill mineral wool is applied to the attic floor. Both air temperatures and surface temperatures are measured to calculate heat flows and to detect convection cells in the loose-fill insulation. The presence of convection cells can be indicated by a scatter in surface temperatures—the more convection, the larger the difference in temperature over the top surface. The measurements on loose-fill insulation in the homogeneous part of the attic floor are presented in this paper, and the measurements on the conventionally constructed attic floor are presently running.

DIMENSIONLESS NUMBERS AND MATERIAL PROPERTIES

The measurements of the thermal performance of the insulation in the attic test model are presented as thermal resistance of the attic floor as a function of a modified Rayleigh number, and Nusselt number as a function of the modified Rayleigh number. The modified Rayleigh number, Ra_m , is a dimensionless number that can be regarded as a measure of the driving forces for natural convection.

$$Ra_m = \frac{g\beta\rho c_p}{\nu} \cdot \frac{dk\Delta T}{\lambda} \quad (1)$$

The properties of the air are the heat expansion coefficient, $\beta = 1/T_{mean}$ 1/K (1/°R); the kinematic viscosity, ν (m²/s, ft²/s); the density, ρ (kg/m³, lb/ft³); and the specific heat capacity, c_p (J/kg, Btu/lbF). The air permeability of the porous material is denoted k (m², ft²), the thermal conductivity of the insulation without convection λ (W/mK, Btu·in./h·ft²·F), the thickness of the insulation d m (ft), the temperature difference across the insulation ΔT (°C, °F), and the acceleration due to gravity g (m/s², ft/s²).

The Nusselt number compares the amount of heat flow with convection to the amount of heat flow without convection, for the same situation. When the Nusselt number exceeds unity, convection has started.

$$\text{Nu} = \frac{\text{heat flow with convection}}{\text{heat flow without convection}} \quad (2)$$

In order to calculate the modified Rayleigh number, several properties of the insulation need to be determined: thickness, thermal conductivity, and permeability, and, to determine these properties, the density of the insulation and the mean temperature in the insulation. In the following section, these properties are described.

Insulation thickness

In order to properly determine the thickness of the insulation layer, for both rockwool boards and loose-fill insulation, a thickness meter was constructed according to the ISO draft proposal for loose-fill insulation. The apparatus, a pin gauge, consists of a pin and a pressure plate that exerts a pressure of 30 Pa (4.4e-3 lb/in²). The thickness of the loose-fill insulation in the attic part without joists was measured in June, ten days after the insulation was applied, and then in November after the tests were completed in this part of the attic. The settling amounted to 1% of the thickness. The initial thickness in the metering area was 0.405 m (1.33 ft), ranging from 0.392 to 0.411 m (1.29 ft to 1.35 ft).

Density and Density Variations

After the tests on loose-fill insulation were completed, the thickness in the metering area was measured and the insulation in this area was removed and weighed. The density of the loose-fill insulation was determined to be 31.1 kg/m³ (1.94 lb/ft³), which agreed well with the requested density of 30 kg/m³ (1.87 lb/ft³).

Thermal Conductivity as a Function of Density

The thermal conductivity of a porous insulation material is determined by three parameters: conduction in the air, conduction in the solid matrix, and radiation across the pore surfaces and convection. As a function of density, this can be described as follows, assuming that the material is dry (no effect of latent heat) and that the air is still (no convection), which is a correct assumption when the heat flow is downward.

$$\lambda = \lambda_{air} + \lambda_{solid} + \lambda_{rad} = A + B\rho + \frac{C}{\rho} \quad (3)$$

Thermal conductivity as a function of density for the rockwool, loose-fill insulation in the attic test model has been determined by using information from Jonsson (1995) and Dyrbøl (1998). Their measurements are fitted, using Equation 3, to $\lambda(\rho) = \lambda(30) = 0.0429 \text{ W/mK}$ [$\lambda(\rho) = \lambda(1.87) = 0.297 \text{ Btu} \cdot \text{in}/\text{h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$], which is the thermal conductivity of the loose-fill insulation measured at SP. The fitted curve is shown in Figure 2.

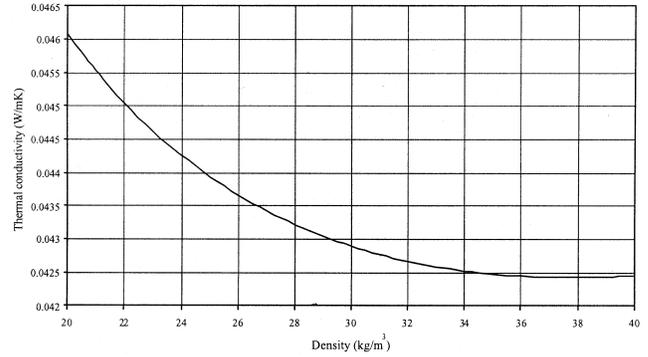


Figure 2 Estimated curve for the thermal conductivity as a function of density for loose-fill rockwool insulation.

The density of the loose-fill insulation in the attic model within the metering area was 31.1 kg/m³ (1.94 lb/ft³) for the attic part without joists. Since the thermal conductivity of the loose-fill insulation has been measured at SP at a density of 30 kg/m³ (1.87 lb/ft³), the accuracy of the approximation of thermal conductivity as a function of density is not critical. The difference in thermal conductivity between a sample of 30 kg/m³ (1.87 lb/ft³) and 31.1 kg/m³ (1.94 lb/ft³) is merely $\pm 0.5\%$.

Thermal Conductivity as a Function of Mean Temperature

Heat transfer in a material depends on the mean temperature of the material. A decrease in temperature leads to a lower thermal conductivity of the air in the pores of the material and to a decrease in radiation between the pore sides, thus, to a lower thermal conductivity of the material.

Measurements of the thermal conductivity of the loose-fill insulation used in the attic test model have been performed at different mean temperatures at SP. The thermal conductivity of the loose-fill insulation has been measured at a density of 30 kg/m³ (1.87 lb/ft³) and at a temperature difference across the sample of 20°C (36°C). The temperature-dependent thermal conductivity can be expressed as

$$\lambda = 258 \cdot 10^{-6} \cdot T_{mean} + 0.04031 \text{ W/mK}, \quad (4)$$

$$[\lambda = 995 \cdot 10^{-6} \cdot T_{mean} + 0.24769 \text{ Btu} \cdot \text{in}/(\text{h} \cdot \text{ft}^2 \cdot ^\circ\text{F})]$$

Insulation Permeability

The permeability of a material with unidirectional flow is described by Darcy's law,

$$\nabla P = -\frac{\eta}{k} \mathbf{v}, \quad (5)$$

where ∇P Pa (lbf/ft²) is the pressure gradient, η (Ns/m², lb/fts) is dynamic viscosity, k m² (ft²) is permeability, and \mathbf{v} (m³/m²s or m/s, [ft/s]) is the seepage velocity. For one-dimensional, steady-state conditions we get

$$\frac{P}{d} = \frac{\eta}{k} \cdot \frac{R}{A} \quad (6)$$

TABLE 1
Permeability of Rockwool, Loose-fill
Insulation at Two Densities

	Density kg/m ³ (lb/ft ³)	Permeability m ² (ft ²)
Sample 1	30 [1.87]	$9.6 \cdot 10^{-9}$ [$1.0 \cdot 10^{-7}$]
Sample 2	33 [2.06]	$7.1 \cdot 10^{-9}$ [$7.6 \cdot 10^{-8}$]

Here, the seepage velocity is replaced by the total airflow, R (m³/s, ft³/s), divided by the flow area, A (m², ft²). The permeability of the rockwool, loose-fill insulation used in the attic test model has been measured at SP according to SS 02 15 50, modified for loose-fill insulation, and with a stated accuracy of 5%. Two samples were measured.

In order to determine the variation in the permeability due to density variations, permeability equations for rockwool boards from Jonsson (1995) were fitted to the two permeabilities above. This procedure is described in Wahlgren (2001). The equation for the loose-fill insulation that matches the measured data for permeability is

$$k(\rho) = \frac{3.83 \cdot k(32)}{\left(\frac{\rho}{32}\right)^{3.2}} = \frac{5.12 \cdot 10^{-4}}{\rho^{3.2}} \quad (\text{m}^2). \quad (7)$$

This equation is a good estimate of the permeability when the densities are close to the measured values in Table 1.

COMPUTER SIMULATIONS

To help interpret the measurements in the attic test model, computer simulations have been made using the three-dimensional, transient program PConvBoxT (Hagentoft 2000; Hagentoft and Serkitjjs 1995). This program calculates heat flows, air flows, and temperatures in a porous medium with natural convection. The influence of various boundary conditions and of different porous materials can be investigated. Forced convection, moisture flow, or latent heat transfer is not included in the simulations. Air movements are detected by studying the heat flows and the temperature profile on the upper, cold surface.

The attic is simulated as a box of insulation with an underlying board, three insulated walls, and one adiabatic wall (symmetry versus the attic part with joists). The top surface is permeable and in contact with an air gap. According to Serkitjjs (1995), this air gap can be assumed to have a constant thermal resistance of 0.2 m²K/W (1.1 ft²·F·h/Btu). The simulations of rockwool, loose-fill insulation have a density of 31 kg/m³ (1.9 lb/ft³), a thickness of 0.405 m (1.33 ft), and the material properties described in the previous section. The temperature on the warm side, being the lower surface of the board, is kept at a temperature of 22°C (72°F), and the attic air temperature varies with a minimum of -20°C (-4°F). With these input data for the rockwool loose-fill insulation in the attic test model, the maximum modified Rayleigh number is 10. Consequently, the simulations at higher modi-

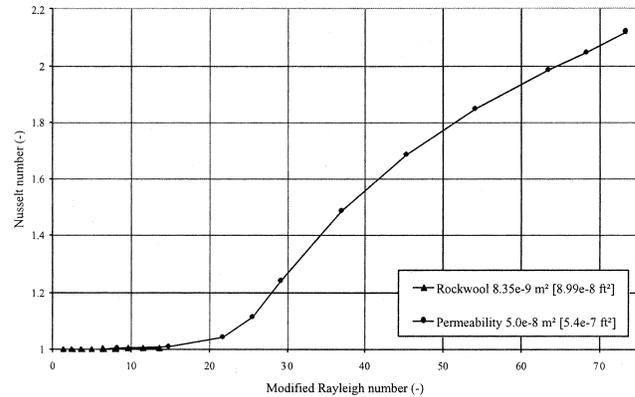


Figure 3 Simulated Nusselt number as a function of modified Rayleigh number for rockwool, loose-fill insulation in the attic test model, calculated over the whole attic floor.

fied Rayleigh numbers represent lighter and more permeable products.

The transient simulation model shows that for this particular attic model setup and for a modified Rayleigh number of 30 it takes approximately eight hours for convection to fully develop, and that a modified Rayleigh number of 60 requires fourteen hours. After this initial phase, stable cells are created in the case of moderate modified Rayleigh numbers, and moving, irregular cells are created at high modified Rayleigh numbers (larger than 60); see Figure 4. The Nusselt number as a function of the modified Rayleigh number in Figure 3 has been calculated after the initial convection buildup and according to Equation 2.

The modified Rayleigh number is calculated using the temperature difference from the lower surface of the board to the top surface of the insulation, which is what is measured in the attic test model. The coldest conditions in the attic test model result in a maximum modified Rayleigh number for the rockwool insulation of 10 and a Nusselt number of 1.002, i.e., a negligible increase in heat flows through the attic insulation.

In order to investigate the influence of the structure of the material on convection, simulations were made on three different material structures having the same overall thermal conductivity and permeability. The three material structures were: lumps of insulation in a more permeable material, lumps that are more permeable in a less permeable material, and homogeneous material. It was shown that by representing the loose-fill insulation with a nonhomogeneous material, the critical modified Rayleigh number and the Nusselt number could be both decreased and increased. Investigations into how to properly model the structure of the loose-fill material are needed. The influence of a density gradient in the insulation was also simulated. The density variation was determined from measurements on the rockwool, loose-fill insulation used in the attic test model, and the effect of the gradient on the Nusselt number was small.

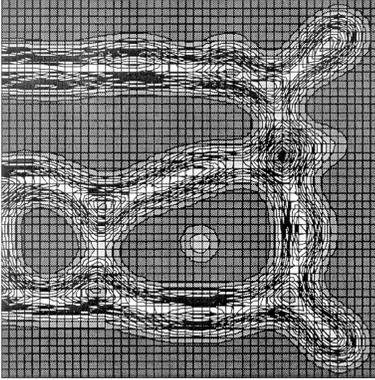


Figure 4a Horizontal temperature profile, $Ra_m = 62.7$.

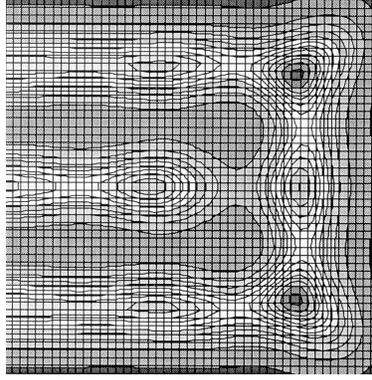


Figure 4b Horizontal temperature profile, $Ra_m = 34.6$.

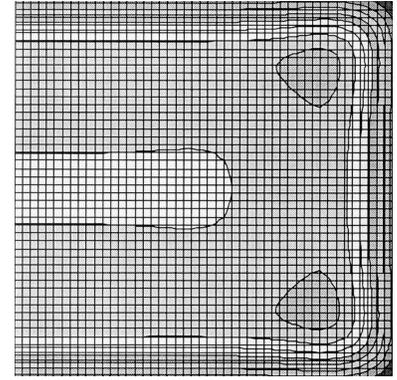


Figure 4c Horizontal temperature profile, $Ra_m = 13.6$.

The temperature profile on the upper surface of the insulation shows different patterns depending on the magnitude of the convective forces. At high modified Rayleigh numbers, the pattern changes with time and is irregular (Figure 4a), whereas moderate modified Rayleigh numbers result in stable cells (Figure 4b). At low modified Rayleigh numbers, there is little or no convection (Figure 4c). The horizontal temperature profile is calculated at 2.5 cm (0.98 in.) below the insulation surface, i.e., in the center of the top calculation node.

The presence of convection cells can be indicated by a scatter in surface temperatures; the more the convection, the larger the difference in temperature over the top surface. The simulations in Figure 5 show higher horizontal temperature differences in the top node (2.5 cm [0.98 in.] below the surface), divided by the total temperature difference, for increasing modified Rayleigh numbers. The temperature difference is determined within the metering area as the highest temperature minus the lowest temperature.

Both temperatures and heat flows vary at different locations under the attic floor. Therefore, simulations were made to investigate the influence of the location of the metering box on the estimated thermal resistance of the attic floor. The simulations showed that it is important to simulate the correct location of the metering box, in particular at high modified Rayleigh numbers when the direction and the magnitude of the air flow varies greatly over the attic floor.

ERROR ANALYSIS OF THE MEASUREMENTS

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

$$\Delta F = \left| \sum_{k=1}^n \frac{\partial F}{\partial x_k} \Delta x_k \right| \quad (8)$$

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

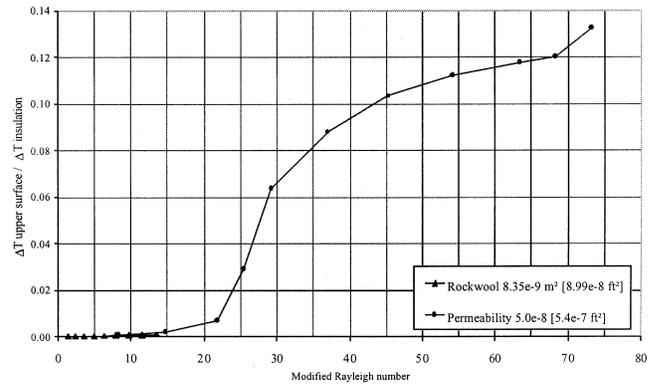


Figure 5 Simulated temperature difference over a horizontal surface divided by the temperature difference over the attic insulation and board, as a function of the modified Rayleigh number.

$$\frac{\Delta Ra_m}{Ra_m} = \left| \frac{\Delta d}{d} \right| + \left| \frac{\Delta k}{k} \right| + \left| \frac{\Delta(\Delta T)}{T} \right| + \left| \frac{\Delta \lambda}{\lambda} \right| \quad (9)$$

The maximum error for each parameter is as follows: thickness of the insulation $1 \cdot 10^{-3}$ m ($3.3 \cdot 10^{-3}$ ft), permeability 5% (according to SP), temperature difference 0.1°C (0.18°F), and thermal conductivity 3% (according to SP). With the temperature difference used in the attic test model (20°C to 45°C , 36°F to 81°F) and an insulation thickness of 0.4 m (1.31 ft), the maximum relative error in the modified Rayleigh number is between 8% and 9%. The influence of this error on the Nusselt number (using 8%) is illustrated in Figure 6 for a simulation on a highly permeable insulation material. For a modified Rayleigh number of 30, the error in the Nusselt number is larger than 10%, while for a modified Rayleigh number of 20, the error in the Nusselt number is only a few percent.

The measured thermal resistance has been calculated according to

$$R = \frac{A_{\text{box}} \cdot \Delta T_{\text{attic floor}}}{Q_{\text{attic floor}}} \quad (10)$$

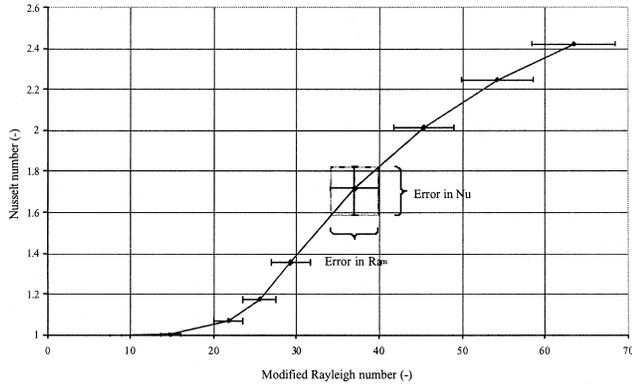


Figure 6 An example of the effect of an error in modified Rayleigh number on Nusselt number.

where A_{box} (m^2 , ft^2) is the metering area of the box, $1.006 m^2$ ($10.8 ft^2$); $\Delta T_{attic\ floor}$ ($^{\circ}C$, $^{\circ}F$) is the temperature difference across the attic floor, from the upper surface of the insulation to the lower surface of the particleboard; and $Q_{attic\ floor}$ (W , Btu/h) is the heat that passes through the attic floor.

The total error in measured thermal resistance is calculated similarly to the error in the modified Rayleigh number using Equation 8 on Equation 10, which results in

$$\frac{\Delta R}{R} = \left| \frac{2\Delta l}{l} \right| + \left| \frac{\Delta(\Delta T)}{\Delta T} \right| + \left| \frac{\Delta Q}{Q} \right| \quad (11)$$

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. For the loose-fill insulation in the attic test model, the highest modified Rayleigh number is 10. The error in thermal resistance for this measuring situation is 8.1% and at a modified Rayleigh number of 4.8, the error in thermal resistance is 7.3%.

The measured thermal resistance has been compared to a calculated thermal resistance based on thermal conductivity values, $\lambda(T_{mean})$, from SP according to

$$R = \frac{d}{\lambda(T_{mean})}. \quad (12)$$

The maximum relative error in calculated thermal resistance is

$$\frac{\Delta R}{R} = \left| \frac{\Delta d}{d} \right| + \left| \frac{\Delta \lambda(T_{mean})}{\lambda(T_{mean})} \right|. \quad (13)$$

With an error in thermal conductivity of 3% (according to SP) and an error in thickness of $1 \cdot 10^{-3} m$ ($3.3 \cdot 10^{-3} ft$), the error in calculated thermal resistance is 3.2% for a thickness of 0.4 m (1.31 ft).

MEASUREMENT RESULTS

The results of the measurements in the attic test model are presented using three different properties: thermal resistance,

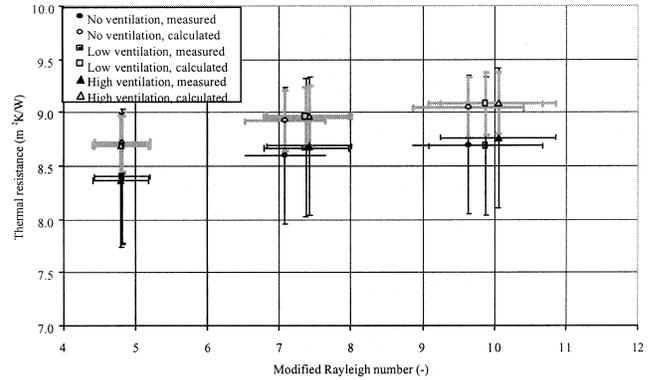


Figure 7 Measured and calculated thermal resistance for homogeneous loose-fill insulation including error bars for thermal resistance and for modified Rayleigh number.

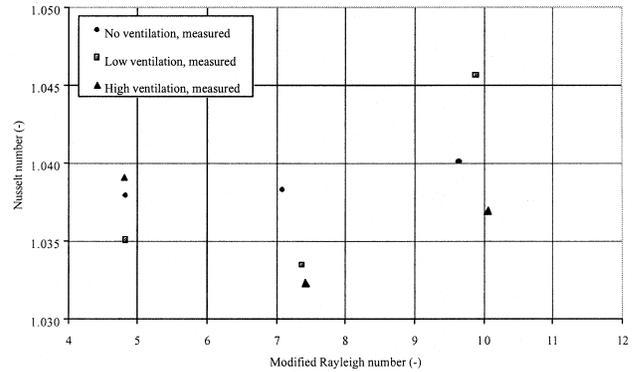


Figure 8 Measured Nusselt number as a function of modified Rayleigh number for homogeneous loose-fill insulation in the attic test model.

the Nusselt number, and the scatter in temperatures at the upper surface. The measured thermal resistance (including convection) has been compared to a calculated thermal resistance (without convection). Since the metering box is placed in the middle of the attic, there is no need to include the thermal bridges that the walls constitute. This has been further investigated in Fryklund (1997b). The measured and the calculated thermal resistance differ by approximately 4%; thus, the calculated and measured thermal resistances are within the margin of error. Figure 7 shows the calculated thermal resistance, according to Equation 12, and the measured thermal resistance, Equation 10, with error bars. For the measured thermal resistance an error of 7.5% is used, for the calculated thermal resistance 3.2%, and for the modified Rayleigh number 8%.

Figure 7 shows that the ventilation rate only has a minor effect on the measured thermal resistance at the prevailing airflows and modified Rayleigh numbers. The Nusselt number as a function of the modified Rayleigh number (Figure 8) shows a slight increase in the Nusselt number with an increase

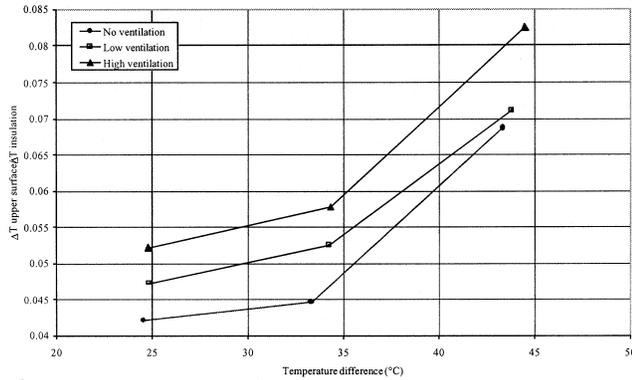


Figure 9 Temperature difference on the top surface of the insulation divided by temperature difference over the attic floor, as a function of the latter.

in the modified Rayleigh number. (The Nusselt number is calculated by dividing Equation 11 with Equation 10.) However, since the thermal resistances are within the margin of error, natural convection in the material is not proven even though the Nusselt number is larger than one. The dip in the Nusselt number that occurs at a modified Rayleigh number of approximately 7 to 8 is also found in the simulations but at a slightly higher modified Rayleigh number of approximately 10.

For the loose-fill insulation in the attic area without joists, a higher ventilation rate results in a larger temperature scattering, expressed as $\Delta T_{upper\ surf.} / \Delta T_{insulation}$, and a slightly lower mean temperature at the upper surface of the insulation. Furthermore, the measured scattering increases nonlinearly with the modified Rayleigh number (Figure 9), while simulations show a linear and much smaller dependence at the prevailing modified Rayleigh numbers. This indicates air movements in the material during the measurements. However, an exact comparison between simulated and measured scatter is difficult since the simulations assume a completely homogeneous material while the loose-fill insulation consists of loosely packed lumps. The thermocouples on the upper surface are all covered with a lump of insulation; nevertheless, the measurement situation for each thermocouple is not identical—a scatter in temperatures is expected even at low modified Rayleigh numbers. Figure 10 shows the measured upper surface temperature profiles with and without attic ventilation. The wind protection in the attic space, over which the ventilation air passes, ends shortly before the metering area, approximately 10 cm above the insulation surface. This causes a smaller decrease in surface temperatures close to the exhaust, where the surface is protected by wind deflectors, and a larger decrease further away from the air entrance (see Figure 10).

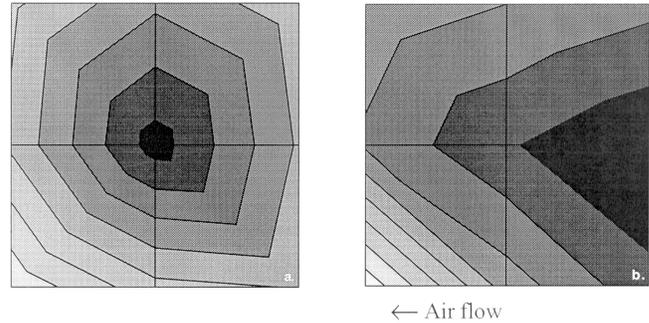


Figure 10 Temperature profiles on the upper surface of the insulation within the metering area, the darker the color, the warmer. There are eight thermocouples on the periphery of the area and one in the center. The figures represent (left) no ventilation and (right) a low ventilation rate (forced convection).

CONCLUSIONS

Measurements in a large-scale attic test model insulated with Swedish loose-fill insulation, and simulations, have been presented. The purpose of the measurements is to determine whether there is convection in the insulation and, if so, the effect that convection has on the heat flows through the insulated attic floor. The measurements show that the thermal resistance of the attic insulation is approximately 4% less than the calculated resistance based on standard measured thermal conductivities. This discrepancy is within the margin of error. Air movements in the insulation are indicated by a scatter in measured surface temperatures at the upper surface of the insulation. However, at the prevailing modified Rayleigh numbers, the air movements are insufficient to cause a decrease in the thermal resistance of the attic floor, which is shown in both measurements and simulations.

ACKNOWLEDGMENT

This project is being financially supported by the Swedish Council for Building Research (BFR/FORMAS), which is greatly appreciated. The research is being carried out under the guidance of Professor Carl-Eric Hagentoft and Professor Claes Bankvall.

NOMENCLATURE

A	= area (m ² , ft ²)
d	= thickness (m, ft)
g	= gravitational acceleration (m/s ² , ft/s ²)
k	= air permeability (m ² , ft ²)
l	= length (m, ft)
Nu	= Nusselt number

P	= pressure (Pa, lb/ft ²)
Q	= heat flow (W, Btu/h)
R	= thermal resistance (m ² K/W, ft ² h ^o F/Btu)
R	= airflow (m ³ /s, ft ³ /s)
Ra	= Rayleigh number
T	= temperature (°C, °F, °R)
v	= seepage velocity (m ³ /m ² s or m/s, or ft ³ /ft ² s or ft/s)
λ	= thermal conductivity (W/mK, Btu·in/h·ft ² ·°F)
η	= dynamic viscosity (Ns/m ² , lbfs/ft ²)
ρ	= density (kg/m ³ , lb/ft ³)

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