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Paula Wahlgren

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Overview and Literature Survey of Natural and Forced Convection in Attic Insulation

PAULA WAHLGREN*

Department of Civil and Environmental Engineering
Division of Building Technology, Chalmers University of Technology
412 96 Gothenburg, Sweden

ABSTRACT: This article presents an overview and a literature survey of convection in attic insulation. The study focuses on the onset of natural convection in the insulation, but also discusses the influence of forced convection. It covers experimental studies in small-scale measurement apparatus, large-scale laboratory measurements, *in situ* measurements, as well as numerical and theoretical work on convection in attic insulation. Suggestions for future work are also presented.

KEY WORDS: convection, attic, insulation, heat transfer.

INTRODUCTION

IN COLD CLIMATES, well-insulated building components are beneficial both to the environment and to the individual homeowner. In Sweden, for example, ≈40% of the total energy use is related to buildings and 70–90% of this energy is consumed during the occupation phase of the building (Adalberth, 2000). In order to obtain a good thermal performance, insulation materials with adequate thickness and properties and good workmanship are required. Loose-fill insulation is commonly used in residential buildings, in particular on attic floors. The main advantage of loose-fill insulation compared to insulation boards is that the installation procedure is easy and fast. The loose-fill insulation is blown into place, pipes and other installations are easily covered and there is little waste. However, the air permeability of loose-fill insulation is often higher than that of insulation boards, which can allow for air movements, convection, in the insulation.

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*Author to whom correspondence should be addressed. E-mail: paula.wahlgren@chalmers.se

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Natural convection occurs in wintertime and is triggered by air density differences due to temperature differences. The warmer air at the bottom rises and the colder, denser air sinks due to gravity. This takes place both in the attic insulation and in the attic space, and the result is an increase in heat transfer through the attic floor. Air movements due to an external driving force, such as wind, is referred to as forced convection. Forced convection includes the case when air moves along the upper surface of the insulation (wind swept insulation) and the case when air penetrates the insulation, often due to poor function of the wind protection boards. An example of an attic with loose-fill insulation, wind protection along the eaves, and ventilation is shown in Figure 1. Wind protection boards have various designs and can be made of different materials, such as cardboard, plastic foam, or mineral wool. There is usually no wind protection at the upper surface of the insulation.

There are several consequences when convection occurs in insulation. Primarily, the air movements cause extra heat loss through the insulation, resulting in higher energy use and, possibly, a poor thermal comfort in the building. Convection can also influence moisture distribution in the attic. A good understanding of convection makes it easier to determine the required insulation material properties for a construction, and also to design, for example an attic, so that natural or forced convection does not decrease the thermal performance. A certain construction or insulation material might be suitable in a moderate but not in a colder climate. Consequently, reliable information on convection is essential to assess materials, constructions, and suitable climate zones.

Research on convection in air-permeable attic insulation has been performed since the eighties. Initially, small-scale measurements were performed, both on natural and forced convection. In the nineties, measurements were

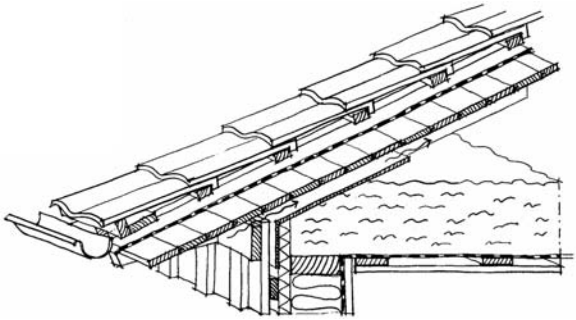

Figure 1. *An example of a ventilated attic with loose-fill insulation and wind protection at the eaves.*

also carried out in attic modules where, for example, joists, wind protection boards, and other details could be included. Numerical models were developed parallel to this work.

This article presents a review of the literature about measurements and simulations of convection in attic insulation. The study focuses on the onset of natural convection, but also discusses the influence of forced convection. It covers experimental studies in small-scale measurement apparatus, large-scale laboratory measurements, *in situ* measurements, and numerical and theoretical work on convection in attic insulation.

A background is given to present the theory on convection in porous materials and also to guide the reader from the basic case with convection in a horizontal, homogeneous medium with well-defined boundary conditions, to the situation in an attic.

BACKGROUND AND DEFINITIONS

Convection is one of the three heat transfer modes in insulation, the others being conduction and radiation. Convection is the action of conveying and in the present context it is moving air that transports heat. There are two types of convection, natural convection and forced convection. Forced convection is caused by an external airflow and can be induced by, for example, attic ventilation. Natural convection occurs due to density differences between cold and warm air. In attic insulation, the air at the bottom of the insulation layer is heated and rises, whereas the air at the top layer sinks. The onset of natural convection in attic insulation is a stability problem. In a wall, the air moves upward at the warm side and downward at the cold side.

The modified Rayleigh number is a dimensionless number that can be regarded as a measure of the driving forces of natural convection. The larger the modified Rayleigh number, the stronger the driving forces of natural convection. The modified Rayleigh number is a function of the properties of the air in the material and the properties of the material, and is calculated as:

$$\mathrm{Ra_m} = \frac{g\beta\rho_f c_{p,f}}{\upsilon} \cdot \frac{\mathrm{d}k\Delta T}{\lambda_m}(-). \tag{1}$$

The properties of the air are heat expansion coefficient, β (1/K), kinematic viscosity, $\nu(\mathrm{m^2/s})$, density, ρ_f ($\mathrm{kg/m^3}$), and specific heat capacity, $c_{p,f}$ (J/kg K). The properties of the insulation material are air permeability, k ($\mathrm{m^2}$), and thermal conductivity, λ_m ($\mathrm{W/m \cdot K}$). The temperature difference over the insulation (from warm side to cold side) is ΔT (°C) and d (m) is the thickness of the insulation.

To denote the onset of convection, the critical modified Rayleigh number, $\mathrm{Ra}_{\mathrm{m,cr}}$, is used. The critical modified Rayleigh number depends on several factors, most importantly the boundary conditions and the geometry of the material. According to linear stability analysis, an infinite layer of horizontal homogeneous porous material with impermeable and isothermal upper and lower surfaces has a critical modified Rayleigh number of $4\pi^2$. Changing the upper surface to permeable (which corresponds to an attic) reduces the critical modified Rayleigh number to 27.1. Further reduction is obtained when the thermal conditions at the upper and lower surfaces are changed to constant heat flow, which decreases the critical modified number to 3.

When natural convection develops in a homogeneous porous layer, different types of cells can form. Experiments, presented in Zierep and Oertel (1982), show hexagonal convection cells that are created with a permeable upper boundary, and rolls with an impermeable upper boundary. Lower boundaries are impermeable. This is shown in Figure 2(a) and (b).

In attic insulation there are inhomogeneities in the insulation, such as joists, cavities, and pipes. Cavities can be caused by poor workmanship, but also by people, or by mice living in the insulation. Poor performance of

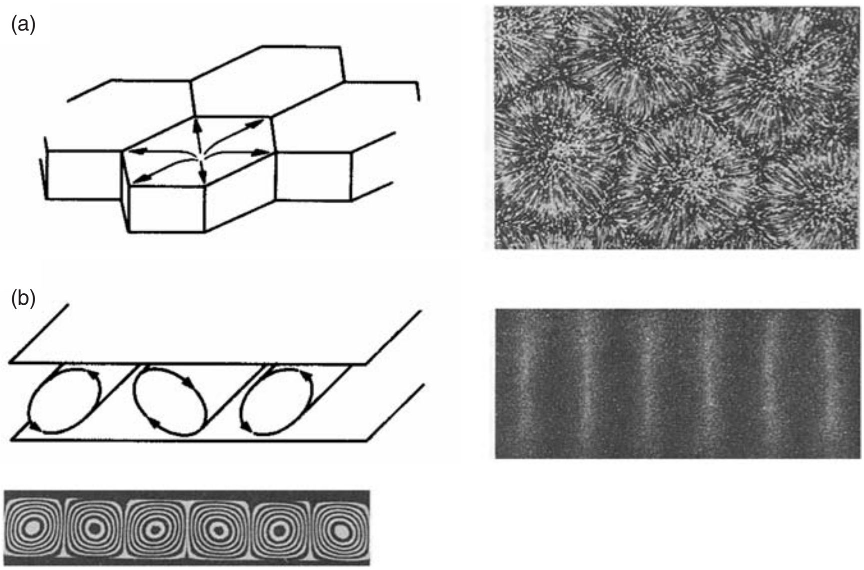

Figure 2. *(a) Hexagonal convection cells, streamlines visualized with aluminum powder. (b) Convection rolls, horizontal and vertical visualization (from Zierep and Oertel, 1982).*

the wind protection has caused the insulation to move in some attics. Usually, these inhomogeneities will be of great importance to the shape of the convection cells, resulting in more complex cells.

The insulation material itself is not always homogeneous, which affects the thermal conductivity and the air permeability of the insulation. The effect of material anisotropy (different property values in different directions) on the critical modified Rayleigh number has been studied by Epherre (1977) for impermeable and isothermal boundaries. He shows how the critical modified Rayleigh number varies when the material properties in horizontal and vertical direction are different. Corresponding work for other boundary conditions are presented in McKibbin (1986). Furthermore, Epherre presents the minimum critical modified number as a function of the thermal conductivity ratio and air permeability ratio according to Equation (2).

$$\xi = \frac{k_{\mathrm{H}}}{k_{\mathrm{V}}} \qquad \eta = \frac{\lambda_{\mathrm{H}}}{\lambda_{\mathrm{V}}}$$
$$\mathrm{Ra}_{c,\,\min} = \pi^2 \left[1 + \left(\frac{\eta}{\xi} \right)^{1/2} \right]^2. \tag{2}$$

An illustration of the effect of anisotropy is made, using material data from Dyrbøl (1998). She measured the following material properties for rockwool boards with an average density of 30.5 kg/m^3; horizontal and vertical thermal conductivities, $\lambda_{\mathrm{H}} = 0.0383$ (W/m · K), $\lambda_{\mathrm{V}} = 0.0352$ (W/m · K), horizontal and vertical air permeabilities, $K_{\mathrm{H}} = 28.0 \cdot 10^{-10}$ (m^2), and $K_{\mathrm{V}} = 17.4 \cdot 10^{-10}$ (m^2).

These material properties result in a critical modified Rayleigh number of 32.8. For an isotropic material, a corresponding critical modified Rayleigh number (impermeable and isothermal boundaries) is 39.4 ($4\pi^2$). Consequently, the anisotropy here resulted in a 17% reduction in the critical modified Rayleigh number.

For an attic insulation, there are many reasons why it is difficult to determine a critical modified Rayleigh number. In order to take into account effects caused by joists or cavities, numerical simulations or measurements are required (these are described below). When introducing a joist (solid inclusion with higher thermal conductivity than the insulation), the result is that the stability in the fluid/porous medium system is disturbed so that convection can start easier, i.e., at lower modified Rayleigh numbers. The perimeter of the attic floor can be colder than the center of the attic floor which also affects the stability of the system. Furthermore, in an attic configuration the boundary conditions are not easily described and they may also be dynamic. The geometry of the attic is also important to the critical modified Rayleigh number and several geometrical aspect ratios are significant. An example is the height of the joists in the attic floor in relation to the height (thickness) of the insulation. All these factors make it difficult to predict a critical modified Rayleigh number for an attic. Moreover, when natural convection starts in an attic insulation, the initial effect on heat transfer is sometimes very small and it can be difficult to estimate the critical modified Rayleigh number. It is also important to bear in mind that the radiative heat transfer through a material depends on the mean temperature in the material. If the mean temperature changes during the test procedure it is possible that an increase in convective heat transfer is concealed by a decrease in radiative heat transfer.

Although the focus of this work is to discuss the onset of natural convection in attic insulation a brief description of how the heat flows are affected by natural convection is given.

The increase in heat flow due to natural convection can be described by the Nusselt number, Nu. The Nusselt number is the ratio between the heat flow through the insulation with convection and the heat flow without convection, for the same situation.

$$\mathrm{Nu} = \frac{Q_{\text{with convection}}}{Q_{\text{without convection}}} (-). \tag{3}$$

There are estimations of the relation between the Nusselt number and the modified Rayleigh number (representative of the driving forces for natural convection). Cheng (1978) presents a compilation of experimental, analytical, and numerical results for a horizontal, homogeneous layer heated from below. For most investigations, liquids are used in combination with porous material created by spheres (e.g., glass beads). Critical modified Rayleigh numbers close to 40 were found. The following relation for the Nusselt number and the modified Rayleigh number is suggested by Elder (1967).

$$\mathrm{Nu} = \frac{\mathrm{Ra_m}}{40} (-). \tag{4}$$

Wang and Bejan (1987) constructed the following formula to correlate with measured data.

$$\mathrm{Nu} = \left\{ \left(\frac{\mathrm{Ra_m}}{40} \right)^n + \left[c \left(\mathrm{Ra_m}\, \mathrm{Pr_p} \right)^{1/2} \right]^n \right\}^{1/n} (-). \tag{5}$$

Here, n and c are two empirical constants, $n = -1.65$ and $c = 1896.4$, and, $\mathrm{Pr_p}$, is the porous medium Prandtl number according to

$$\mathrm{Pr_p} = 0.72 \cdot \frac{\lambda_f}{c_\mathrm{F}\lambda_m} \cdot \frac{d}{\sqrt{k}}(-). \tag{6}$$

This porous medium Prandtl number is valid when the moving fluid is air. A value of 0.55 can be used for the form-drag constant, c_F, for many materials of high porosity.

Measurements, simulations, and suggested formulas for natural convection in homogeneous insulation are assembled in Figure 3 (based on Wahlgren, 2002b). The configuration is a horizontal layer with impermeable and isothermal boundaries. Two sets of measurements on homogeneous loose-fill insulation (Langlais et al., 1990; Serkitjis, 1995) are compared to numerical simulations (Delmas and Wilkes, 1992; Fryklund, 1995) and to estimations of the Nusselt number as a function of the modified Rayleigh number (Equations (4), (5) and Bankvall, 1981).

The formula suggested by Bankvall (1981) is

$$\mathrm{Nu} = 1 + 0.04 \cdot (\mathrm{Ra_m} - 40)^{0.88}. \tag{7}$$

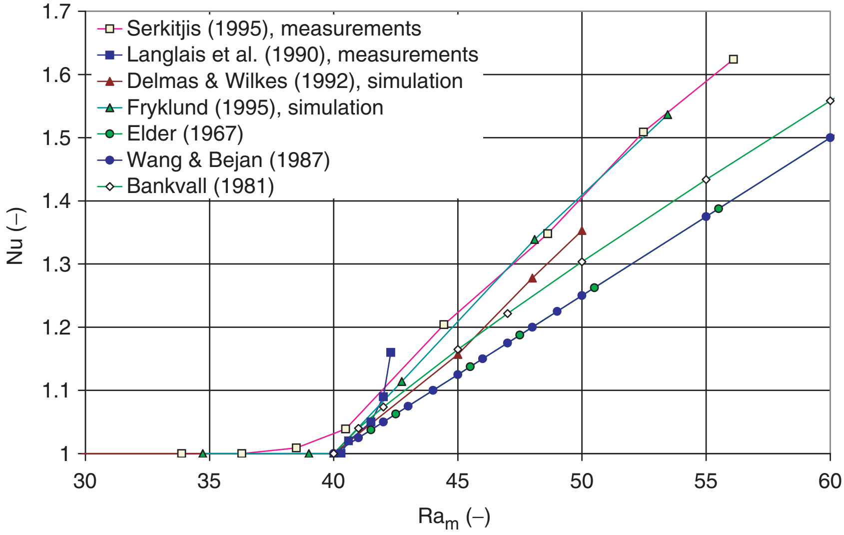

Figure 3. *Nusselt number as a function of modified Rayleigh number for a homogeneous insulation layer bounded by isothermal and impermeable surfaces. Compilation of measurements, simulations, and estimations (based on Wahlgren, 2002b).*

In most of the following work, natural convection is described in terms of Nusselt number as a function of critical modified Rayleigh number or of the temperature difference across the attic floor. In some studies, the thermal resistance of the attic floor is used. Without natural convection, the thermal resistance is fairly constant and independent of the temperature difference across the attic floor. Once natural convection starts in the insulation, this is shown as a decrease in thermal resistance.

The thermal resistance, R, of the attic floor is defined by

$$R = \frac{\Delta T}{Q} \cdot A \quad (\mathrm{m^2\,K/W}) \tag{8}$$

where ΔT (°C, K) is the temperature difference between the warm side and the cold side, Q (W) is the heat flow through the attic floor, and A (m^2) is the area.

Forced convection is often presented as a Nusselt number that is a function of wind velocity along the upper surface of the insulation.

For further reading on convection in porous media, Nield and Bejan (1999) is recommended. A summary of the critical modified Rayleigh numbers for attic floors obtained in different studies are presented in Table 1.

MEASUREMENTS

As discussed in the previous section, there are many parameters that affect the onset of natural convection and the convective air movements in attic insulation. Numerical simulations are useful tools to study convection and they are usually less time consuming and less expensive than measurements. However, numerical simulations need to be confirmed against measurements in order to ensure that the important parameters are included. Laboratory measurements are also estimations of real attics subjected to climate variations. Large-scale measurements better simulate real attics than small-scale measurements for several reasons. The geometry (including size) of the attic is important to the development of natural convection. The shape and size of the convection cells are different for different geometries, which affects the onset of convection. The air volume above the attic insulation, the attic space, is also of importance to convection, not the least when forced convection is studied.

In this survey, measurements that have a sample area of $3 \times 3\,\mathrm{m}^2$ or less are classified as small-scale measurements. Usually, the measurement area is smaller than $3 \times 3\,\mathrm{m}^2$ since there is a guard area around the

Table 1. Investigations of natural and forced convection aiming to understand convection in attic insulation.

	Configuration			**Measurements**			**Numerical simulations**		**Critical modified Rayleigh number**
References	**Attic (joists, roof slopes)**	**Boundary condition (Permeable/ impermeable)**	**Natural convection/ Forced convection**	**Full scale/ *in situ***	**Large scale**	**Small scale (sample< 3 × 3 m^2)**	**3D**	**2D**	**Natural convection (yes or no) Critical modified Rayleigh number when estimated**
Anderlind (1992)	yes	p	n,f	*X*					No
Besant and Miller (1983)	no	p,i	n,f			*X*			Yes
Ciucasu et al. (2005)	yes	p	n					*X*	28
Delmas and Arquis (1995)	joists	p	n		*X*			*X*	10–27
Delmas and Wilkes (1992)	joists	p,i	n		*X*			*X*	8–27 permeable 30 impermeable
Jonsson (1993)	no	p,i	n			*X*			3 permeable 5 impermeable
Langlais et al. (1990)	no	p,i	n,f			*X*		*X*	30 permeable 30–40 impermeable
Löfström and Johansson (1992)	yes	p	n,f	*X*					No
Rose and McCaa (1991)	yes	p	n,f	*X*					Yes
Serkitjis et al. (2001)	joist	p	n,f			*X*			10^a, 20^b no joist 8^a joist
Serkitjis and Hagentoft (1998)	no	p,i	n			*X*	*X*		24 permeable 40 impermeable
Serkitjis (1995)	no	p,i	n			*X*	*X*		20 permeable 40 impermeable
Silberstein et al. (1990)	no	p,i	n,f			*X*			15 permeable 30–40 impermeable

(*continued*)

Table 1. Continued.

	Configuration			Measurements			Numerical simulations		Critical modified Rayleigh number
References	Attic (joists, roof slopes)	Boundary condition (Permeable/ impermeable)	Natural convection/ Forced convection	Full scale/ *in situ*	Large scale	Small scale (sample< $3 \times 3\,m^2$)	3D	2D	Natural convection (yes or no) Critical modified Rayleigh number when estimated
Silberstein et al. (1991)	no	p,i	f			*X*		*X*	
Wahlgren (2005b)	yes	p	n				*X*		9–25
Wahlgren (2004)	yes	p	n		*X*		*X*		22–23 measurements 24–27 simulations
Wahlgren (2002a)	yes	p	n,f		*X*			*X*	22–23 measurements 27 simulations
Wahlgren (2001)	yes	p	n,f		*X*			*X*	22–23 measurements 27 simulations
Wahlgren et al. (2001)	joists	p	n					*X*	10
Wilkes et al. (1991a)	yes	p	n		*X*				Yes
Wilkes et al. (1991b)	yes	p,i	n,f		*X*				13–20 permeable
Wilkes and Rucker (1983)	yes	p	n,f		*X*			*X*	10–30

[a], [b]material A and B

measurement area. The measurement principle for natural convection in a small-scale apparatus is to have a warm lower surface and a cold upper surface with the porous insulation in between and to increase the temperature difference so that natural convection can be detected. Natural convection is identified either by a non-linear increase in heat transfer through the insulation, or by studying the surface temperatures. Boundary conditions vary, and both open and closed upper surfaces are studied. In some studies, forced convection is simulated by blowing air along the upper surface. There are also small-scale investigations on how joists in the insulation affect convection.

Using large-scale or full-scale measurements make it possible to study effects of numerous construction details. Furthermore, the workmanship when applying the insulation material can be similar to that at a construction site. Large-scale measurement equipment for attic insulation are often built in climate chambers, where the temperatures and the ventilation air speed can be controlled. In the same way as small-scale measurements, convection in large-scale and full-scale equipment is detected by studying heat flows and temperatures.

Small-scale Measurements

Small-scale measurements for horizontal insulation have been made by Besant and Miller (1983), Jonsson (1993), Langlais et al. (1990), Serkitjis (1995), and Silberstein et al. (1990, 1991). Besant and Miller (1983) found that the loose-fill insulation had a decrease in thermal resistance with an increase in temperature difference over the insulation. Jonsson (1993) presented measurements where natural convection started slightly already at a modified Rayleigh number of 3 for a permeable upper surface and at 5 for an impermeable upper surface, both being non-isothermal. Langlais et al. (1990) showed that convection starts as soon as a temperature gradient is applied over the insulation, but that a significant effect on the thermal resistance of the material is obtained only for modified Rayleigh numbers close to the theoretical value. They defined a critical modified Rayleigh number of 30 for an open specimen, which is in good agreement with the theoretical value of 27.1 for the corresponding setup. Serkitjis (1995) obtained a critical modified Rayleigh number of $\approx$20 with a permeable upper surface and 40 with an impermeable upper surface. The test material in this case consisted of polystyrene pellets. Using the same equipment, two mineral wools were also tested and the modified Rayleigh numbers dropped to 10 (Serkitjis et al., 2001). When a joist was introduced into the insulation, the critical modified Rayleigh number was only slightly lowered, to 8.

Investigations on forced convection, in the same paper, show that the more permeable the material, the greater the influence of air velocity on heat transfer through the material. A joist in the insulation further increases the heat transfer. Measurements from Silberstein et al. (1990) showed that the critical modified Rayleigh number was ≈15 for a permeable homogeneous specimen with natural convection, but that air movements were present even at lower modified Rayleigh numbers. The investigations on forced convection by Silberstein et al. (1991) showed that there is little effect of forced convection when the airflow is $<0.5\,\mathrm{m/s}$, and that there is a decrease in thermal resistance with increased air velocity. Nevertheless, all presented investigations, using small-scale measurements, show that there is a small increase in heat transfer due to forced convection as soon as there is airflow over the material.

Full-scale, *in situ* Measurements

Convection in attic insulation does not only depend 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. This motivates studies of attic insulation in full-scale or with large-scale equipment under realistic climate conditions. Full-scale, *in situ* measurements of the thermal resistance of attic insulation have been performed by Anderlind (1992), Löfström and Johansson (1992), and Rose and McCaa (1991). Anderlind (1992) and Löfström and Johansson (1992) made measurements at low modified Rayleigh numbers only and found no significant effect of natural convection on the thermal resistance of attic insulation. Rose and McCaa used materials with a higher air permeability, and natural convection started in the insulation. The decrease in thermal resistance of the attic floor insulation due to forced convection was negligible.

Large-scale Laboratory Measurements

A large-scale laboratory measurement is the most suitable method to experimentally estimate natural and forced convection in attics. The surrounding climate is controlled and large-scale effects can be studied. The most recent experimental studies are described in Wahlgren (2001, 2002a, 2004). Measurements using large-scale laboratory equipment (described in Fryklund, 1997), with and without attic ventilation, are presented. The investigations showed that natural convection started in the insulation when the modified Rayleigh number exceeded 22. A comparison between the measured thermal resistance at the onset of convection and the thermal resistance at the maximum measured modified Rayleigh number showed a decrease of ≈25% in thermal resistance. The measurements also indicated that attic ventilation has an effect on convection in the insulation material. Wilkes and Rucker (1983) published the first large-scale laboratory measurements of convection in attic insulation. They concluded that natural convection occurred in the insulation and that the critical modified Rayleigh number was much lower that the theoretical value. The work was continued by Wilkes et al. (1991a,b). They found that the thermal resistance of loose-fill insulation was up to a factor of two lower than the nominal thermal resistance, due to natural convection. The critical Rayleigh number in Wilkes et al. (1991b) was estimated to be between 13 and 20. Attic ventilation did not affect the thermal resistance of the attic floor.

SIMULATIONS

A number of numerical simulations have been made to examine the phenomena of convection in attic insulation and to perform parametric studies. In recent times, numerical studies of convection in attic insulation have been made by means of computational fluid dynamics (CFD). Wahlgren (2004) uses three-dimensional CFD-simulations of the experimental setup described in, for example, Wahlgren (2001a) to compare numerical and experimental results, with good agreement. A critical modified Rayleigh number of 24–27 was simulated and 22–23 was measured. The CFD-simulations are validated in Wahlgren (2005a). Two-dimensional simulations using the finite difference method were earlier used for the same purpose, and the simulated critical modified Rayleigh number with this method was 27. Ciucasu et al. (2005) used two-dimensional CFD-simulations to illustrate natural convection in attic insulation. The critical modified Rayleigh number was 28 for the investigated setup, using three different insulation materials. Wahlgren (2005b) used three-dimensional CFD-simulations to investigate the variation in onset of natural convection in attic insulation due to changes in insulation material and in the geometry of the attic. The critical modified Rayleigh number varied greatly and a range of 9–25 was obtained in the simulations.

Two-dimensional numerical studies that concern the influence of joists on natural convection in attic insulation, are presented in Delmas et al. (1992, 1995). They showed that the critical modified Rayleigh number is lowered when joists are introduced into the insulation material. To what extent is determined by, among other factors, the distance between the joists and the height of the insulation. Critical modified Rayleigh numbers from 8 to 27 are obtained for permeable upper surfaces. At higher modified Rayleigh numbers, the joists become an obstacle to motion. Another two-dimensional example of the effect of the joists is shown in Wahlgren et al. (2001). The introduction of a joist in a horizontal insulation resulted in a decrease in critical modified Rayleigh number from 25 to 10. However, even with the joist, the additional heat flow due to convection was small at modified Rayleigh numbers below 25. At large modified Rayleigh numbers the joist acts as an obstacle to convection.

An example of a three-dimensional numerical study with homogeneous insulation material is presented in Serkitjis and Hagentoft (1998). The simulations are based on a finite difference method and show good agreement with the measurements in Serkitjis (1995).

OVERVIEW OF THE STUDIES

A summary of the described investigations is presented in Table 1. The column denoted ‘attic’ tells if the studied configuration has the shape of an attic with a ceiling, joists, and wind protection boards at the eaves connected to an outer roof. The other configurations are horizontal homogeneous insulation or horizontal insulation with joists. The boundary condition at the upper surface is described in terms of permeable or impermeable. The column ‘critical modified Rayleigh number’ states the estimated critical modified Rayleigh number, if such is available, or answers if natural convection has been detected or not (yes or no). The studies are presented in order of scale of the used measurement equipment, and ends with numerical studies without measurements. Within each group, the papers are presented chronologically.

DISCUSSION

As described earlier, there is a great variation in the reported critical modified Rayleigh numbers. This is partly due to a large variation in construction (including size and attic space), material properties (and structure), workmanship, and boundary conditions, but also due to measurement techniques and differences in numerical simulations.

For the measurements that have an attic configuration, the critical modified Rayleigh number range from 10 to 30. Accordingly, there is no

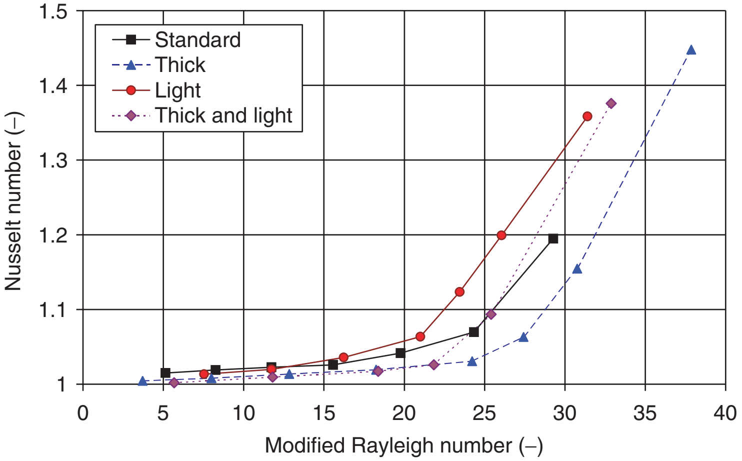

Figure 4. *Nusselt number as a function of the modified Rayleigh number for an attic (Wahlgren, 2005b).*

general critical modified Rayleigh number that can be used for all attics. Neither is there a general formula for the Nusselt number as a function of the modified Rayleigh number available for attics. In some cases, when the critical modified Rayleigh number is exceeded (i.e., natural convection has started), there is only a small increase in heat transfer through the attic floor. The net effect of convection on the total heat flows through the attic floor, and on the energy use, depends on the duration of the cold weather conditions. Cold weather and natural convection during a short period of time causes only a small increase in annual energy use. On the other hand, thermal comfort in the building might be affected and need to be taken into account.

Figure 4 shows examples of three-dimensional simulations of one attic construction (with joists and wind protection boards), in which the insulation material and the insulation thickness are changed (Wahlgren, 2005b). The attic floor is insulated with two loose-fill insulation materials (standard, $\rho = 15\,\mathrm{kg/m^3}$, and light, $\rho = 9.4\,\mathrm{kg/m^3}$), having two insulation thicknesses (standard, 0.4 m, and thick, 0.6 m). Onset of natural convection is different for the different cases, even though the construction of the attic is exactly the same, and there is no influence of forced convection. Furthermore, the increase in heat flow is also different for the different cases. The simulated insulation material is homogeneous, i.e., there is no anisotropy and the workmanship is perfect so that no cavities are created, for example behind the joists.

This example clearly shows that care needs to be taken before drawing any conclusion on the onset of natural convection, even for a specific attic.

RECOMMENDATIONS

Even though convection in attic insulation is a complex phenomenon without distinct limits, there is some advice that can be used to minimize the risk of convection and lessen the negative consequences of convection in attic insulation.

- When given a choice, the use of very low-density insulation materials should be avoided in cold climates. Very low-density insulation materials have higher air permeability and are thus more susceptible to convection.
- Great care should be taken to workmanship when applying the insulation material. This ensures a minimum of cavities and leakage paths in the insulation. These can act both as initiators of natural convection and increase heat transfer in the case of convection. Furthermore, damage to the insulation should of course be prevented.
- Careful installation and a proper design of the wind protection boards along the eaves are important. This prevents the ventilation air from entering directly into the insulation and minimizes the risk that the ventilation air blows away the insulation. The long-term performance of fastening devices should be secured.

FUTURE WORK

A large amount of work has been made on the subject of convection in attic insulation. However, due to the complexity of the phenomenon, there is still a great deal of work worth investigating.

As described, many different critical modified Rayleigh numbers have been reported for attics. Since natural and forced convection in attics strongly depend on the geometry of the attics, it is important to study the phenomenon in large-scale experiments. The ideal scenario would be to have a large-scale attic where all the important parameters (construction, material, etc.) could be changed and where any climate could be used. This would make it possible to investigate the critical modified Rayleigh number and the increase in Nusselt number for different combinations. Admittedly, this is difficult to achieve and an alternative is to study convection by using numerical simulation programs. Naturally, the simulations need to be validated against experiment when possible. Computational fluid dynamics simulations have become a useful tool in this work. However, there are numerous considerations to be made to ensure an accurate result. For example, the geometry, the insulation, the air in the attic space, and the boundary conditions need to be properly described. Three-dimensional simulations are preferred since convection in attic insulation is a three-dimensional phenomenon. This is illustrated in Haupt (2005), along with suggestions for ensuring good quality simulations. The attic space needs to be accounted for in an adequate way, in particular when the attic space is ventilated and the insulation can be subjected to forced convection. And, as for natural convection, the simulations on forced convection also need to be validated against measurements.

As mentioned earlier, many different results have been presented on natural convection in attics. They have all dealt with insulation that has been applied with good workmanship and that has not been damaged (e.g., by wind or mice). Cavities and cracks will affect the thermal performance of the insulation, which is also highly relevant for the case of forced convection. Forced and mixed convection are not investigated as well as natural convection and need to be studied further. In addition to the parameters that influence natural convection, the following details need to be taken into consideration: the geometry of and the ventilation strategy for the attic space, and the design and function of the air inlet and the wind protection boards.

In order to calculate an accurate modified Rayleigh number and to obtain representative values to use in numerical models, the material properties of the insulation need to be well determined. The material property that is most difficult to measure and that yields the largest error is the insulation permeability, in particular for low-density materials. Consequently, it would be beneficial with more accurate methods to measure air permeability.

Moisture convection takes place when the air that moves contains moisture. Moisture convection within insulated building components has mainly been investigated in walls, see for example Riesner et al. (2001) and Økland (1998). In attics, moisture convection leads to a transfer and redistribution of moisture in the attic, which can result in condensation and mold growth. Further research is required.

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