NATURAL CONVECTION IN A SUPERPOSED AIR AND POROUS LAYER WHEN HEATED FROM BELOW

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ABSTRACT

A numerical and experimental study is performed to analyze the influence of natural convection on heat transfer in a composite system comprising a porous material heated from below and an air space situated above this. The numerical model is verified by conducting a number of experiments, on a model material consisting of polystyrene pellets of cylindrical shape, made in the Wind Box. This apparatus is a prototype and has been designed and developed at the Department of Building Physics. In designing the measuring process, calculation of the maximum systematic error has been a control parameter; this is less than 6%.

INTRODUCTION

The existence of a fluid layer adjacent to a layer of fluid-saturated porous medium is a common occurrence in both the natural (geophysical) and industrial environments, including such engineering applications as solar collector with a porous absorber, journal bearings, fibrous and granular insulation where the insulation occupies only part of the space separating the heated and cooled walls, etc.

In a ventilated attic floor, the insulation material will be in contact with an air space and will be exposed to wind effects which influence the thermal insulation capacity of the material. The first limitation made in view of the magnitude of the subject is to ignore forced convection in this study. Heat transfer is studied in a composite system according to figure 1 in which the inclination of the roof is not considered.

The main difference in construction between recent and earlier buildings in Sweden is that the attic floors of recent buildings have a considerably higher degree of thermal insulation. The most common thermal insulation material on attic floors, for both additional insulation and in new construction, is loose fill insulation which has advantages because of its ease of installation. The insulation is delivered in bags and is applied to the attic floor by a special machine. The top surface of the material is left open, i.e. it has no form of protection against wind. Owing to the greater thickness of the material, with 0.5m being a standard application, and the open top surface, there is an increased risk of air movements in the material which will cause a reduction in its thermal insulation capacity.

The object of this work was to chart in detail whether natural convection occurs in isotropic porous materials and what its effects are on the thermal insulation capacity of the material. Both the theoretical and experimental investigation focuses on the factors which influence natural convection in a configuration consisting of a porous material and an air layer.

One important goal was to determine the increase in heat flow due to convection. This is expressed by the Nusselt number, which is defined as the ratio of the heat flow, q (W/m²), with and without convection:

$$Nu = \frac{q_{\text{with convection}}}{q_{\text{without convection}}}$$

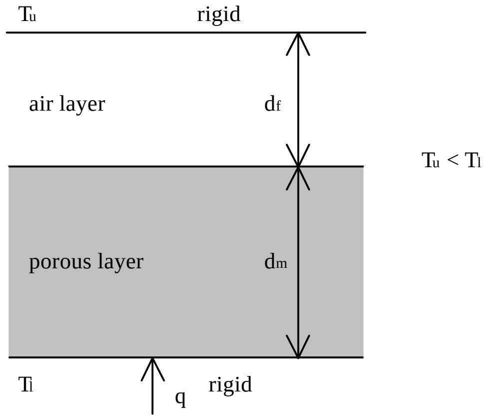

Figure 1 Sketch of the configuration used in the study.

The investigation includes measurements in the Wind Box and calculations with a recently developed computer simulation program (CONVBOX) for three-dimensional convection problems. The research focuses on a model material consisting of polystyrene pellets of cylindrical shape. The combination of simulation and experiments performed in the Wind Box has been found to be an important instrument in understanding the complex coupled convection processes which occur in the insulation material. The completed study is described in greater detail in Serkitjis (1995).

COMPUTER CALCULATIONS

Natural convection for the case with the porous layer consisting of the model material has been theoretically studied using a recently developed simulation program which takes into account the geometry of the Wind Box. This program, CONVBOX, is described in greater detail in Hagentoft and Serkitjis (1995). The program describes three-dimensional convective heat transfer in a composite system under the assumption that Darcy's law holds in the porous layer. The composite system comprises two layers, a porous layer and an air space. In the model, the air space is replaced by a thin surface layer with the thermal resistance R which includes conduction, radiation and convection. The boundary condition at the air/porous-layer interface is either permeable or nonpermeable. The model presupposes that air flow rates or the values of R are small.

The model provides the opportunity to study both natural and forced convection in different geometries. Equations are solved numerically by a finite difference method, which means that the computation region is divided into parallelepiped computation elements. In order that good results may be obtained, temperatures are calculated analytically in three directions between adjacent nodes. Pressure distribution is calculated from an approximate temperature distribution. When the pressure distribution and thus the air flow field have been calculated, a new and more precise temperature field can be calculated. Both pressure and temperature are computed by an iterative method. Computations are continued iteratively until the result is stabilised between two global iterations. During the calculations, the result can be seen on the screen, both by means of the calculated values of the deviations from perfect mass and heat balance, temperatures, Nusselt number and Rayleigh number, and by means of figures which show cross sectional images of temperature distribution in the three orthogonal planes.

The results of calculations can be followed up via three files which contain the following: input data, current Nusselt number and Rayleigh number, and the computed temperature distribution. Computed temperatures can be read and displayed graphically, which makes it possible to study the number and appearance of the convection elements. A Pentium PC, 90 Hz, computes a case with 8,000 computation elements in approximately 4 hours.

For all calculations the geometry of the measuring apparatus has been used, i.e. the length is equal to 1.2 m and the width is equal to 0.6 m. For the thermal resistance situated above, the value 0.2 m²K/W has been used, which represents the thermal resistance of air spaces of thickness varying between 0.1 and 0.5 m, on the assumption that the air is exposed to a temperature difference of 2°C (-1°C and +1°C).

The validity of the model has been tested with reference to a horizontal space filled with a porous material, the assumption being that the boundary surfaces are nonpermeable and isothermal. Theoretical and experimental considerations have shown that natural convection occurs when the modified Rayleigh Ra_m number exceeds the value 40. This is also confirmed by the computer program used, see figure 2. Ra_m is defined as

$$Ra_m = \frac{\left(\rho_0 c_p\right) \cdot g \cdot \beta \cdot d_m \cdot K \cdot \Delta T}{\nu \cdot \lambda_m}$$

ρ_0	density of the air [kg/m^3]
c_p	specific heat capacity of the air at constant pressure [J/kg·K]
g	acceleration due to gravity [m/s^2]
β	coefficient of cubic expansion [K^{-1}]
d_m	height of porous space [m]
K	permeability of porous medium [m^2]
ΔT	temperature difference across the porous medium [K]
ν	kinematic viscosity [m^2/s]
λ_m	thermal conductivity of the porous medium [W/m·K]

The values calculated by CONVBOX have been set out in figure 2. The results of simulations made with the two-dimensional models of Delmas and Wilkes (1992), denoted "ORNL", and those of

Fryklund (1995), denoted "CHConP", are also plotted in the same figure. A comparison of CONVBOX with the results of Delmas and Wilkes and Fryklund shows good agreement.

If the top surface of the porous material is left open, natural convection - according to theory - begins earlier, namely when the value of the modified Rayleigh number approaches 27.1. Calculations made with CONVBOX referred to before, show not only good agreement with the theory but also very good agreement between the results from the different models. See figure 3.

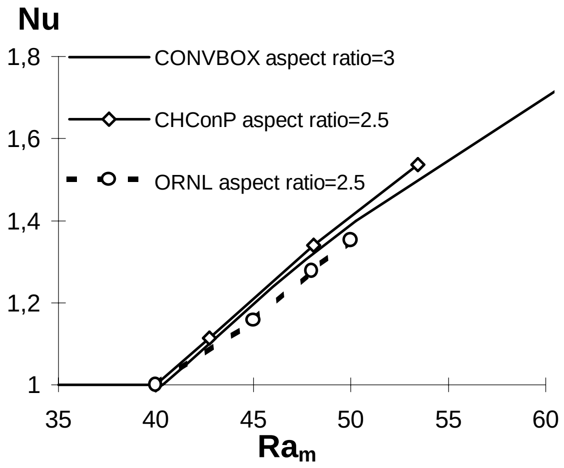

Figure 2 Comparison of the values computed by the program CONVBOX with the simulation programs of Delmas and Wilkes (ORNL) and Fryklund (CHConP). Covered top surface.

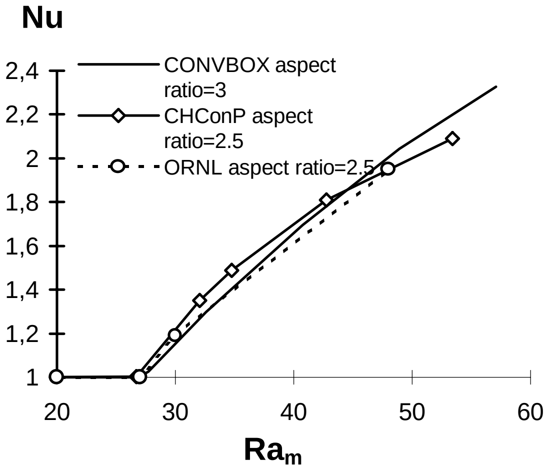

Figure 3 Comparison of values calculated by the program CONVBOX with the simulation programs of Delmas and Wilkes (ORNL) and Fryklund (CHConP). Open top surface.

Convection in the composite system is governed by several parameters, which means that both the theoretical and experimental results are dependent on these. A comparison between theoretical and empirical results can be made for a certain geometry and for a certain combination of porous material and fluid. It is possible to experimentally verify the theoretical results for a specific combination, but it is not clear whether the results can be used for general calculations. There are thus no general correlations in the literature for the composite system. Both theoretical and experimental studies suggest, however, that the value of the critical modified Rayleigh number is below 30.

With the help of CONVBOX, calculations have been made to simulate the course of events for a porous material which is heated from below and whose top surface is in contact with an air space. The influence of an open and a covered top surface has been calculated, and the results of calculations have been plotted in figure 4.

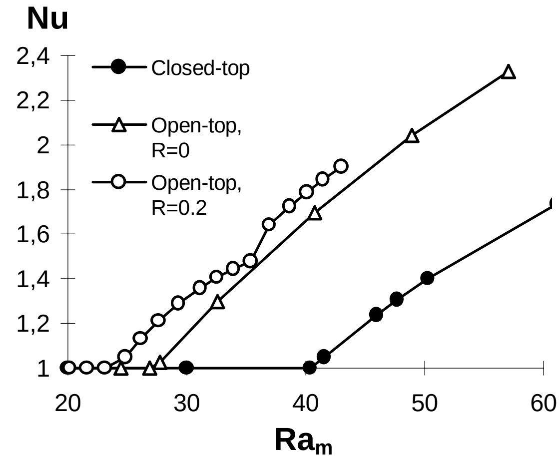

Figure 4 The influence of boundary conditions on convective heat transfer in a composite system comprising an air space and a porous material. The calculations refer to a porous material with $d_m = 0.2$ m, $K = 6 \cdot 10^{-8}\ \mathrm{m}^2$, and $\lambda = 0.044$ W/mK.

The influence of the thermal resistance of the air space and the thickness of the porous material has been calculated and the results are plotted in figure 5. The factors which influence convective heat transfer and which may be of interest for building technology and for experimental investigations are comprised in the definition of the modified Rayleigh number Ra_m. The thermal conductivity, permeability and thickness of the porous material and the temperature difference across the porous

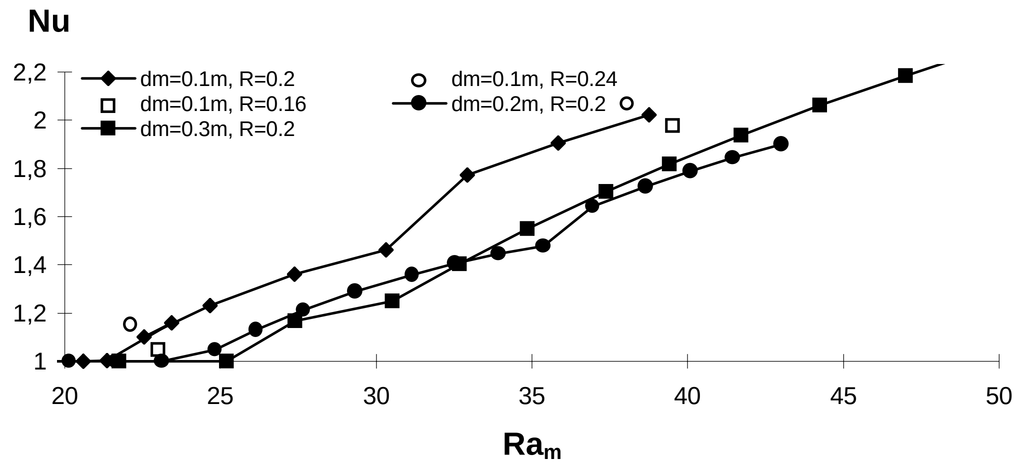

Figure 5 The influence of the thermal resistance of the air space and the thickness of the porous material on heat transfer in a composite system comprising an air space and a porous material ($K = 6 \cdot 10^{-8}\ \text{m}^2$, $\lambda = 0.044\ \text{W/mK}$).

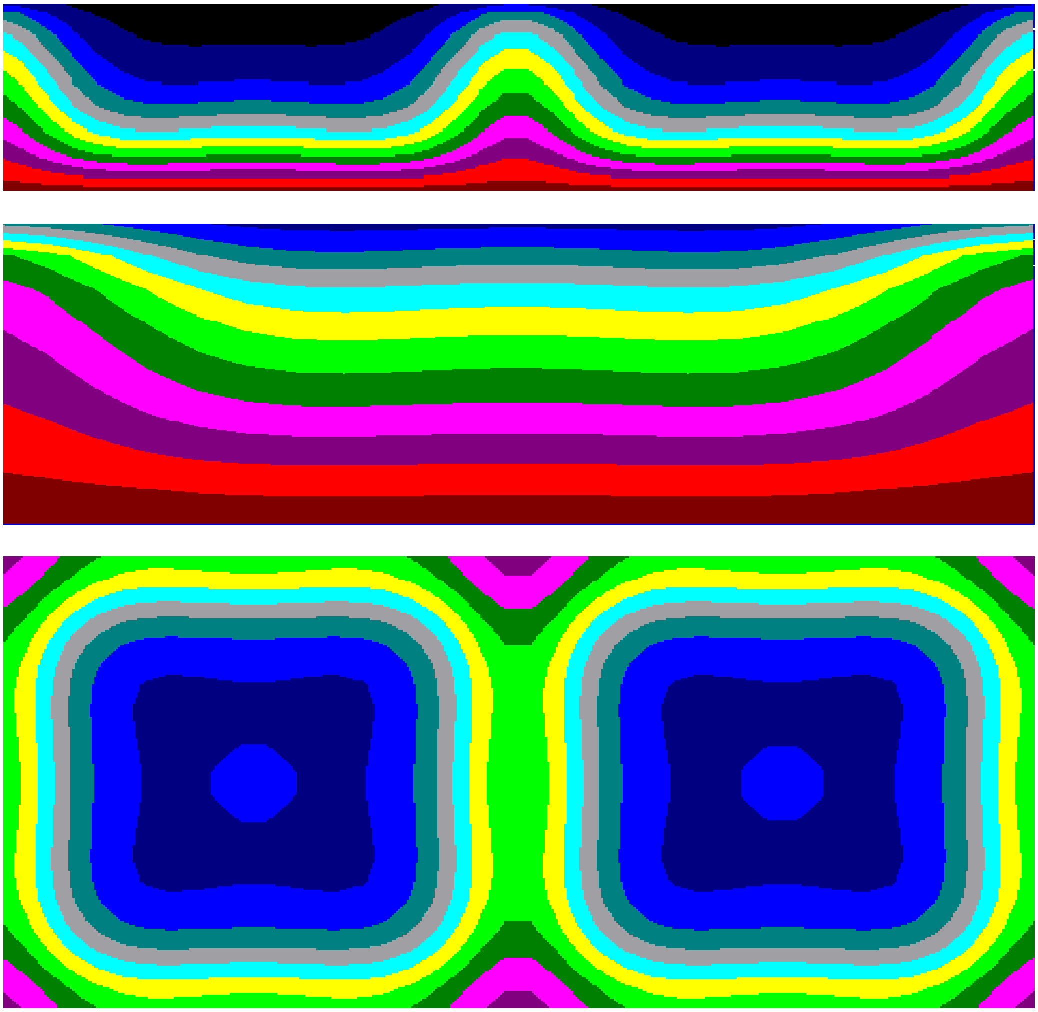

Figure 6 Typical CONVBOX - plots showing three cross sectional images (in the x, y and z directions) of temperature distribution. In this case two square shaped convection elements are formed.

material affect the calculated value of the Rayleigh number and thus convective heat transfer.

For all calculation cases, convection elements of cylindrical shape and parallel to the long side have been formed at low values of the Rayleigh number. These change into a square shape, see figure 6 when the Rayleigh number increases.

EXPERIMENTS

The influence of natural convection on heat transfer through a porous material has been studied for different configurations in the Wind Box. The significance of various factors has been examined with reference to theory and the construction of the measuring apparatus.

Experiments have been carried out on horizontal insulation layers. The conditions for the top surface, open or covered, have been especially focused on. The effect on an overlying air layer with different thickness has also been studied. Some of the results are presented in this paper. Other parameters studied have been thickness, permeability, ambient temperature and the temperature difference across the sample, as well as different combinations of these. All the measurements may be regarded as relative (comparative) measurements, which means that the effect of the systematic error can be ignored.

The principal criteria in choosing the material used in the experiments were that it should have a simple geometry, low density and high permeability. The material should not be hygroscopic or be prone to settlement. The sample material used in the experimental investigation in this paper focuses on a model material that comprises cylindrical polystyrene pellets with hemispherical ends. In order to find out more about the sample material and to provide a sound basis for the calculations, the relevant material properties have been investigated. The results of this investigation are set out in Table 1.

∅ (mm)	Porosity (%)	$\rho\ (\mathrm{kg/m^3})$	$K\ (\mathrm{m^2})$	λ (W/mK)
9.2	33.2	13 - 13.5	$5.5 \cdot 10^{-8}$ - $5 \cdot 10^{-8}$	0.046 - 0.044

Table 1 Summary of the sample material properties.

Owing to the variation in packing density there has been a certain amount of uncertainty in determining permeability and thermal conductivity.

The measuring apparatus, a Wind Box has been designed and developed at the Department of Building Physics. This apparatus is a prototype. The Wind Box is a development of a hot plate apparatus and may be described as a horizontal guarded hot plate apparatus of large measuring area, which is an advantage as insulation thicknesses increase.

Thermal resistance is determined by measuring temperature drops and heat flow rates in a horizontal sample. The thermal resistance can also be determined when air passes over the top surface at different velocities. The general arrangement of the apparatus is shown in figure. 7. The heat supplied to the warm side of the apparatus per unit time can be determined. In order to obtain a measure of the actual heat flow rate, it is necessary to ensure that the flow of all the heat supplied through the sample in one-dimensional. The same temperature is set on the balancing heating foil, the guard sections and the measuring sections, so that all power supplied to the measuring sections passes straight through the sample.

The sample material on the measuring section and the guard sections can be separated by a thin expanded plastics frame which prevents convective heat transfer between these sections. The entire apparatus is enclosed in a chamber equipped with a cooling unit controlled by a contact thermometer. In this way, the temperature of the air surrounding the test apparatus can be adjusted to the mean temperature of the sample (normally +10°C).

A lot of care has been taken with calibration and interference elimination to ensure that the measurements are of high quality. Any errors have been reduced or eliminated when this was possible. One means of control in designing the measuring process was the calculation of the maximum systematic error; this is less than 6%.

For a measurement to be regarded as correct, it is necessary that the balance measured between the measuring plates and guard sections, and between

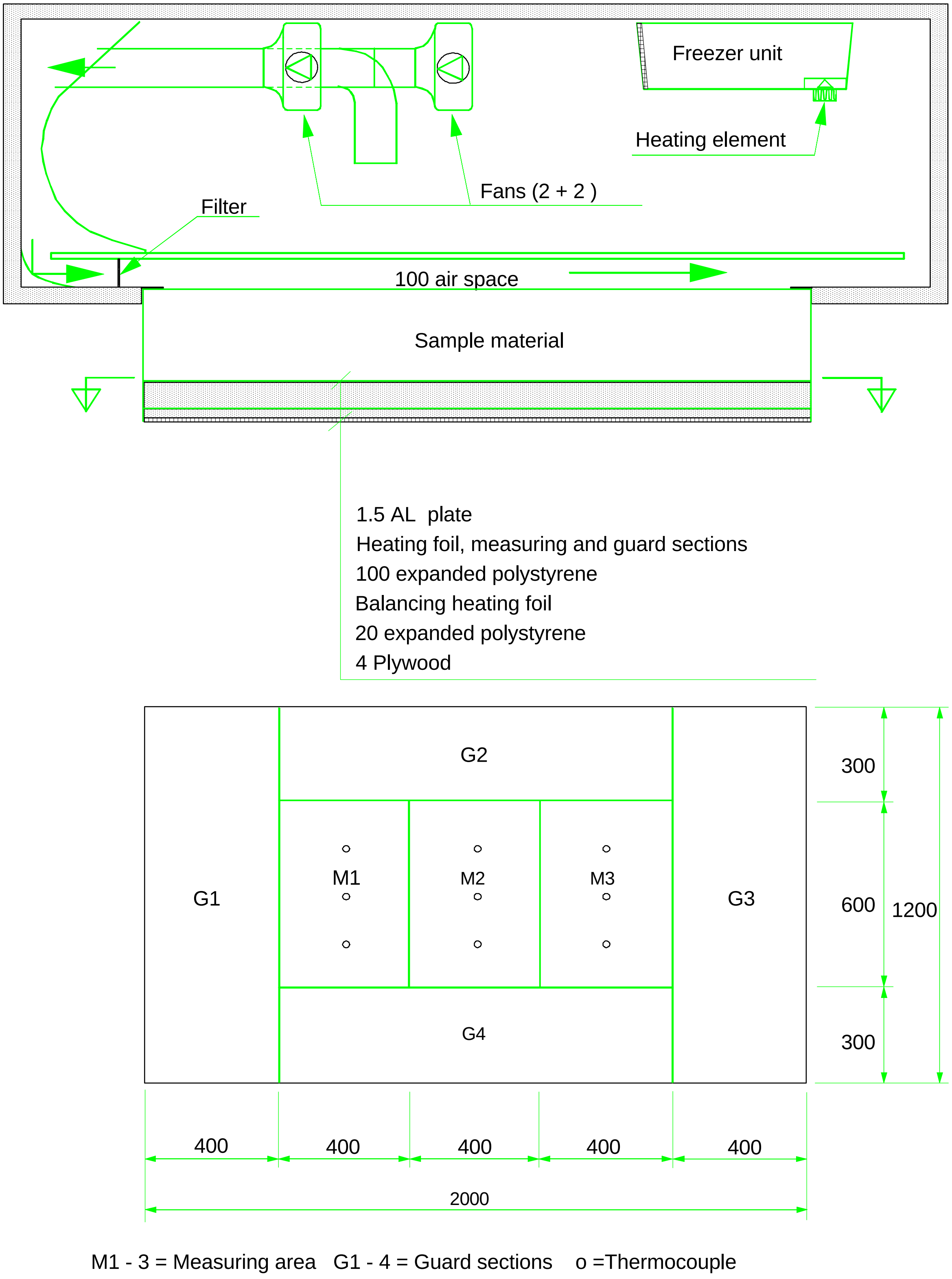

Figure 7 General arrangement of the measuring apparatus. All dimensions in mm.

the measuring plates and the balancing heating foils, does not exceed 0.1°C. Further, the difference between the calculated thermal conductivity and three consecutive measurements at 30 minute intervals shall not exceed 2% or exhibit a tendency to rise or drop.

Measurements made on a 0.3 m thick layer of the pellets, with the top surface covered, show that natural convection starts in the material at $Ra_m = 40$, see figure 8. The results agree with both the theory and experimental investigations made by other researchers. A study of the temperature field inside the material indicates that two-dimensional cylindrical convection cells are formed. This is also in accordance with theory.

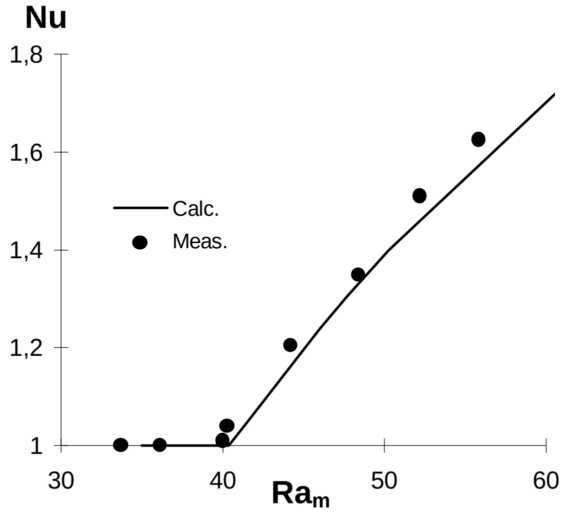

Figure 8 Comparison of calculation results (lines) and measurement results (symbols) for the case with a covered top surface. The measurement results refer to the model material with $\rho = 13\ \text{kg}/\text{m}^3$, d_m =0.3 m at 10°C mean temperature in the sample.

When the combination comprising an air space above the sample material is studied, it is found that the thermal resistance of the air space may be regarded constant. The value of the critical Rayleigh number has been found to be approximately 20, see figure 9. On the basis of measured temperatures, it was possible to identify three-dimensional convection cells (probably square in shape).

CONCLUSIONS

Comparisons with experimental results for natural convection in a homogeneous horizontal insulation material show good agreement. The calculations predict both the right magnitude of the Nusselt number and the critical temperature difference i.e. the temperature difference for the onset of convection, that have been found in the experiments. The results also show good agreement with results found in the literature in terms of critical Rayleigh numbers.

On the basis of calculations and measurements regarding the influence of the air space on the convective component of heat transfer in the underlying insulation, it can be stated that:

- The occurrence of natural convection in the air space has only a marginal effect on heat transfer in the underlying insulation.
- The thermal resistance of the air space may be assumed constant, which means that the air space can be replaced in theoretical models by a constant thermal resistance.
- Alteration of the boundary condition covered top surface, $Ra_{m,c} = 4 \cdot \pi^2$, to an open top surface in contact with an air space halves the critical modified Rayleigh number.
- The ratio d_f / d_m has no critical significance for heat transfer in the insulation.

It may be considered that the available data regarding the validity of the theoretical model are of limited extent for an assessment to be made whether it can be applied more generally. From the comparisons of calculations with measurements on polystyrene pellets, it is evident that the theoretical model holds for this material. It is possible that the geometry of the material may have some influence, which means that the model ought to be tested on other porous materials, such as anisotropic fibrous materials.

The case with forced convection has so far not been studied experimentally. It will be done in a continuation of the project. Both forced and natural convection will be investigated using mineral wool as insulation material.

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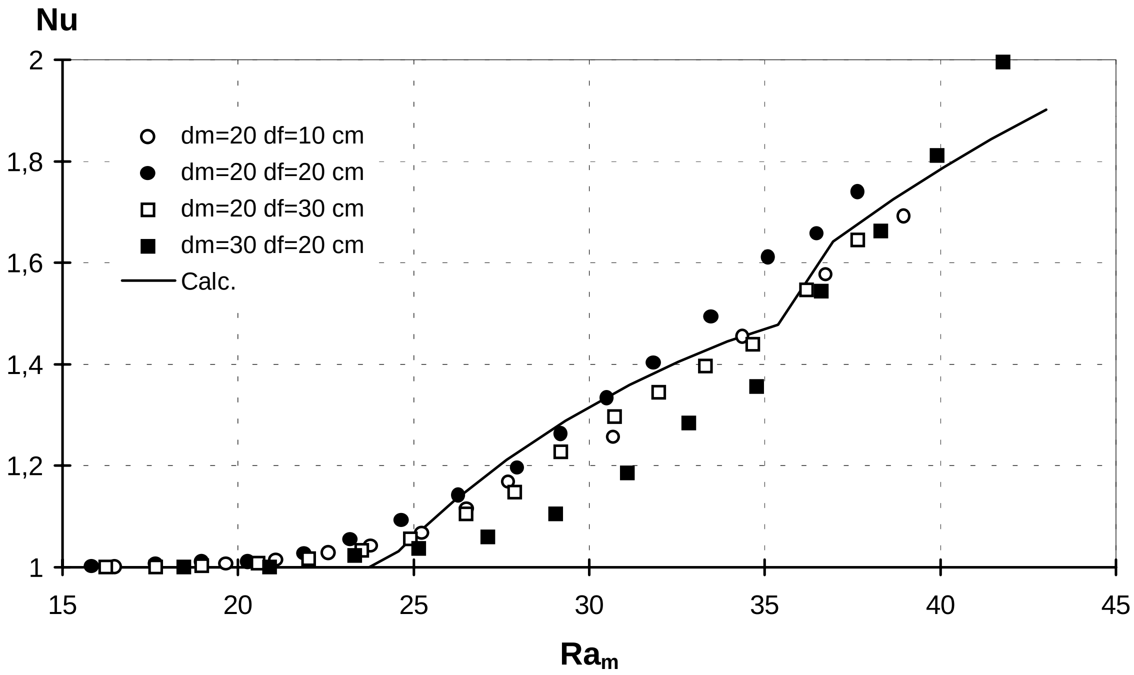

Figure 9 Comparison of the calculation model (Calc.) with measurements made in the Wind Box. The permeability for d_m=0.2 m has been estimated at $K=5.5\cdot10^{-8}$ m^2 and for d_m = 0.3 m at $K = 5\cdot10^{-8}$ m^2. λ = 0.044 W/mK has been assumed for all cases.