Convection in horizontal loose-fill insulation below an air layer

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ABSTRACT: Convection in the insulation material of a building influences the energy efficiency of the building and, in some cases, also the indoor air quality and the durability of the building components. Investigations on horizontal insulation and the thermal effects of natural and forced convection are presented. In particular attic configurations are examined, including different combinations of boundary conditions and material inhomogenities. Both measurements and simulations are used for the investigations.

1 INTRODUCTION

The external construction of a building - the building envelope - must be designed so that a certain specified indoor climate can be achieved in the building. This is reflected by the requirements laid down for the different parts of a building, such as a composite wall construction or an attic floor and a roof. The thermal resistance of a wall or floor depends on the choice of insulation material and the way the construction is designed. In practice, the thermal resistance is also affected by workmanship and by wind conditions around the building.

In both additional and new insulation of attic floors, the most common material in Sweden is loose fill insulation. These materials are porous and thus contain large quantities of air. If the pore system is open, as in mineral wool, air movements can arise owing to the temperature dependent differences in the density of air. These air movements, *natural convection*, cause an increase in heat transfer through the material.

Wind and pressure conditions around a building give rise to air movements outside and inside the building envelope. These air movements, *forced convection*, which are governed by conditions outside the construction such as wind or mechanical ventilation, can also increase heat transfer in the construction.

Owing to the strict Swedish requirements for energy management, there have been great changes in building technology. The insulation thicknesses used now are much larger than before. New constructional details have been developed, and new materials and material grades have appeared. The goal is a structure of high thermal resistance and a building envelope of good airtightness.

These changes have given rise to changed temperature conditions in the different parts of the building envelope. This affects the performance of the materials. Both the durability of the materials and the effect they have on the environment are changed. Even old and tried materials are placed in new climatic situations. The requirements for a building envelope of better thermal performance have also tightened up the requirements regarding workmanship. There is less and less tolerance of substandard work, which detracts from the performance of the material.

Workmanship affects the thermal conductivity of a construction. The way the insulation is placed is obviously very important since the thermal resistance of the insulation material on e.g. an attic floor is more than fifty times as high as that of the air gap that is filled with insulation.

The workmanship employed in insulating the attic floor and the air movements initiated by the wind can in practice exert a critical influence on its thermal conductivity. In order that the thermal performance of the attic floor may be assessed, a combination of measurements and theoretical analyses is often needed, and this requires relevant calculation methods and material data. Loose fill insulations belong to the group of materials for which insufficient basic knowledge is available. In order that these problems may be solved, new models must be constructed to describe heat transfer, for instance in an attic floor exposed to air movements.

2 PROBLEM FORMULATION

2.1 Background

The existence of a fluid layer adjacent to a layer of fluid-saturated porous medium is a common occurrence in both geophysical and industrial environments. The composite systems also 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. Excellent reviews on the subject of the natural convection in composite systems have been presented by Cheng (1978), Prasad (1991), Nield & Bejan (1992) and others.

In the building industry the influence of natural convection on heat transfer has in many cases been disregarded in view of the fact that it is conduction and radiation, which constitute the dominant heat transfer mechanisms for thermal insulation materials. This is true for materials of high density and low permeability. Convection may however be a significant factor in heat transfer in materials of low density and high permeability.

Convection in a composite fluid and packed bed system has traditionally been modelled in two alternative ways. The first and the oldest is the two-domain approach where the porous medium and fluid are treated separately with coupling matching conditions at the interface. In the second kind of scheme the fluid is considered as a special case of a porous medium i.e. both the fluid and porous layers are considered in one domain which does not require any kind of matching at the interface.

The numerical approach reported here treats the fluid and porous regions separately and satisfies the continuity conditions at the interface. The coupled convection and conduction problem was studied theoretically by a computer program using finite difference technique. The theoretical model describes three-dimensional heat transfer in a composite system on the assumption that Darcy's law holds in the porous medium.

2.2 Simplified model

Two computation models for coupled heat conduction and convection steady-state problems have been developed. The two-dimensional model (CHConP) is a general purpose PC-program. Quite arbitrary geometries, build up by the use of rectangular computation cells, can be treated. Anisotropic porous materials can be mixed in the studied structures. Both forced, natural and mixed types of convection problems can be treated, see for instance Fryklund (1995).

The used numerical technique has been implemented in a three-dimensional model (CONVBOX), which treats the problem with a homogeneous porous insulation material in a box of the type used for the experiments, see Serkitjis (1995). The governing equations and the numerical technique are presented by Hagentoft and Serkitjis (1995). The results from simulations are used for comparisons with the experimental results, see Section 3 and 4.

Natural convection for the case with the porous layer consisting of different materials, see Table 1, has been theoretically studied using the CONVBOX. In the model, a thin surface layer replaces the air space with the thermal resistance R that includes conduction, radiation and convection. The boundary condition at the air/porous-layer interface is either permeable or non-permeable. The model presupposes that air flow rates or the values of R are small. 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 m^2K/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 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. In designing the measuring process, calculation of the maximum systematic error has been a control parameter; this is less than 6%, Serkitjis (1995).

Table 1. Density, thermal conductivity and permeability of the materials studied.

Material	Density kg/m^3	Thermal conductivity W/mK	Permeability m^2
Pellets	12.8-13.4	0.045-0.043	5.5-6.5(10^{-8})
Cellulose	32-36	0.035-0.031	2.4-2.6 (10^{-9})
MW1*	8-9	0.055	2.6-2.8(10^{-8})
MW2*	18.5-21.5	0.047-0.043	2.9-1.9(10^{-8})
MW3*	30-34	0.046-042	1.5-2.5(10^{-8})

* Mineral Wool.

2.3 Non-dimensional numbers

For many cases of practical interest, convective heat transfer has been studied and the results are given in the form of equations containing non-dimensional groups. The advantage of using non-dimensional groups is that a large number of variables can be combined into a few non-dimensional parameters. The following non-dimensional parameters are used to describe heat transfer in a porous material:

modified Rayleigh number,

$$\mathrm{Ra_m} = \frac{\rho_0 \cdot c_p \cdot g \cdot \beta \cdot k \cdot d_m \cdot \Delta T}{\nu \cdot \lambda_m},$$

where $\boldsymbol{\rho}_0$ = 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]; $\boldsymbol{\beta}$ = coefficient of cubic expansion [K^{-1}]; d_m = height of porous space [m]; k = air permeability of porous medium [m^2]; ΔT = temperature difference across the porous medium [K]; ν = kinematic viscosity [m^2/s]; $\boldsymbol{\lambda}_m$ = thermal conductivity of the porous medium [W/m·K].

Darcy number,

$$\mathrm{Da} = \frac{k}{d_m^2},$$

Forchheimer number,

$$\mathrm{Fs} = \frac{b}{d_m},$$

where b = coefficient of porous matrix structure property (m).

thermal conductivity ratio,

$$\Lambda = \frac{\lambda_f}{\lambda_m}$$

where λ_f = thermal conductivity of the fluid medium [W/m·K].

In addition to these numbers, aspect ratios, AR, (for example the ratio of insulation thickness to width and the ratio of air layer thickness to insulation thickness), and the type of thermal and hydrodynamic boundary conditions, BC, must be specified. The Nusselt number is the ratio of heat transfer with convection to heat transfer without convection. If there is no convection, Nu = 1, and in other cases its value is greater than 1. Depending on the air flow model used, the Nusselt number becomes a function of different sets of dimensionless numbers:

a) Darcy model,

$$\mathrm{Nu} = f(\mathrm{Ra_m}, \mathrm{AR}, \mathrm{BC})$$

b) Darcy-Brinkman model,

$$\mathrm{Nu} = f\left(\mathrm{Ra_m}, \mathrm{Da}\frac{\tilde{\varsigma}}{\varsigma}, \mathrm{AR}, \mathrm{BC}\right)$$

where η = dynamic viscosity [Ns/m²] and $\tilde{\varsigma}$ = effective viscosity [Ns/m²

c) Darcy-Brinkman-Forchheimer model,

$$\mathrm{Nu} = f\left(\mathrm{Ra_m}, \mathrm{Da}\frac{\tilde{\varsigma}}{\varsigma}, \frac{\mathrm{Fs}}{\mathrm{Pr_m}}, \mathrm{AR}, \mathrm{BC}\right)$$

where $\mathrm{Pr_m}$ is the modified Prandtl number for the porous medium according to

$$\mathrm{Pr_m} = \frac{\eta c_p}{\lambda_m}$$

2.4 Limitations

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 resistance of the material. Heat transfer is studied in a composite system according to Fig. 1 in which the inclination of the roof is not considered. We consider a horizontal porous layer bounded by an impermeable bottom surface while the top surface is open to the surrounding air. Both the bottom and the top temperature is assumed to be uniform. The system is heated from below ($T_l > T_u$).

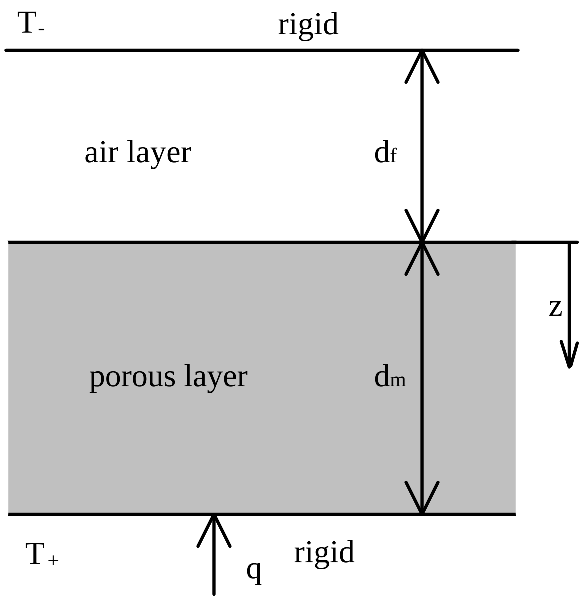

Figure 1. Sketch of the configuration used in the study.

This paper presents investigations on horizontal insulation and the thermal effects of natural and forced convection. The object of this work was to chart in detail whether natural convection occurs in isotropic porous materials and how it effects the thermal resistance of the material. Both the theoretical and experimental investigation focuses on the factors, which influence natural and forced 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.

3 NATURAL CONVECTION

3.1 Porous material, between two isothermal and impermeable plates

Natural convection for a porous material placed between two impermeable plates, the lower plate being warmer than the upper, occurs when the modified Rayleigh number, $\mathrm{Ra_m}$, exceeds the value 40 (4ð^2). This critical limit has been known since 1945 and has been verified both experimentally and theoretically by many researchers, see Serkitjis (1995).

A comparison between calculated and measured Nusselt number as a function of modified Rayleigh number is shown in Figure 2.

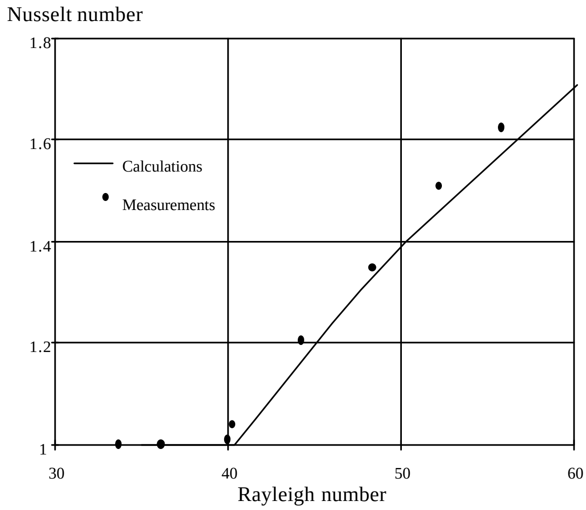

Figure 2. Comparison of calculation results and measurement results for a porous material between two isothermal and impermeable plates.

Calculations are made with the three-dimensional simulation model CONVBOX and measurements are performed on polystyrene pellets in the Windbox. The agreement is good and a comparison of theory with computer calculations and measurements shows that the model works and the measuring apparatus is reliable.

3.2 Porous layer underlying an air layer

For a porous layer underlying an air layer, there are several critical modified Rayleigh numbers for the attic configuration with a lower impermeable and isothermal surface. An impermeable upper surface results in $Ka_{m,cr}$ from 27.1, assuming constant heat flow along the upper surface, to $4p^2$ for an isothermal upper surface as previously described. A permeable upper surface has a critical modified Rayleigh number of p^2 for a constant heat flow, and 27.1 for an isothermal upper surface. The critical modified Rayleigh number also depends on the ratio of insulation thickness, d_m, to fluid layer thickness, a_f. However, measurements on polystyrene pellets with an open surface, in the Windbox, indicate that this ratio has no critical significance for heat transfer in the insulation at the investigated ratios, see Figure 3.

Furthermore, the measurements also show that the occurrence of natural convection in the air space only has a marginal effect on heat transfer in the underlying insulation. A comparison between measurements and calculations, using CONVBOX, is made in Figure 3.

The simulations are performed with a constant thermal boundary resistance of 0.2 m²K/W along the upper surface. According to stability analysis this should result in a critical modified Rayleigh number between p^2 (constant heat flow at the upper surface) and 27.1 (isothermal upper surface). There is a good agreement between calculations and measurements, which indicates that a constant thermal boundary resistance is an adequate assumption.

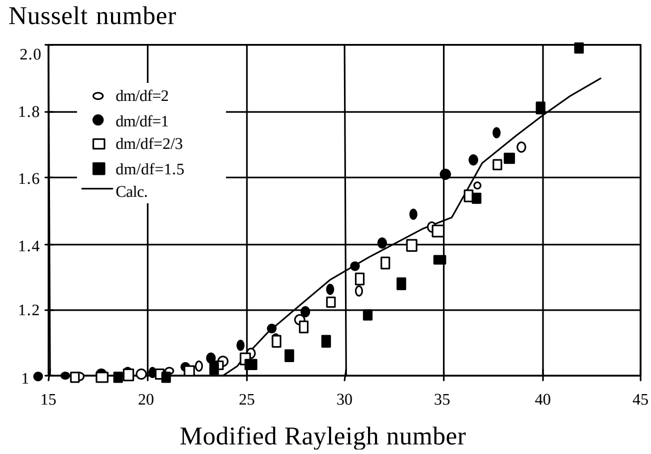

Figure 3. Comparison of calculations and measurements for natural convection in a porous layer with a permeable upper surface.

Measurements are also made on mineral wool and cellulose (see Table 1), which are materials with a more complex structure than pellets. Sample material of 30-cm thickness, with an open top surface, was in contact with an air gap above. A summary of the results obtained is given in Figure 4. Owing to the fact that the critical Rayleigh Number could not be reached for the cellulose, no occurrence of natural convection was recorded in the investigation of this material. It is clear that natural convection in mineral wool begins earlier than in the polystyrene pellets. Since the measurements were made with the same equipment and under similar conditions, the explanation may be found in the differences in material structure. Mineral wool mostly consist of relatively large connected pieces which, on closer study, were found to form considerably larger air spaces between the fractions than was the case for the pellets. In addition, the Darcy number for the pellets is almost three times as large as for the other materials, which might have an effect on the critical modified Rayleigh numbers, and on the Nusselt numbers.

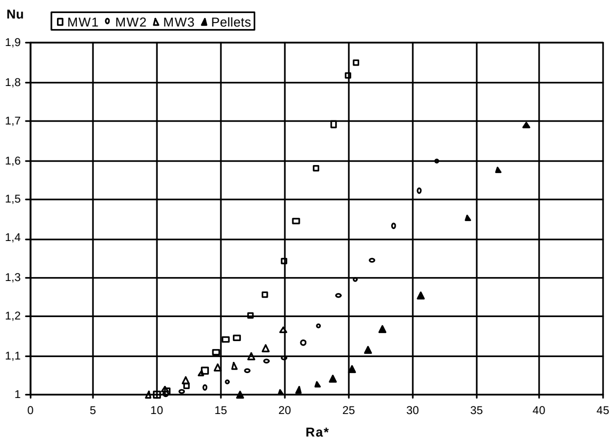

Figure 4. Measured Nusselt number as a function of the modified Rayleigh number for two mineral wool samples and polystyrene pellets with a permeable upper surface.

4 FORCED CONVECTION

Measurements have been made in the Windbox with the same material as was used in the natural convection case, i.e. polystyrene pellets, cellulose and mineral wool. The layer thickness was 30 cm and air was blown into the 10 cm thick air gap above the material at a maximum speed of 3 m/s. The temperature difference across the material was kept constant (at a level lower than that required for natural convection to occur), and in other respects the measurement series were made under identical conditions.

Calculations, using CONVBOX, assume a linear pressure distribution along the upper surface of the insulation. The slope of the pressure for different air velocities, *u*, was calculated as follows:

$$f \cdot \frac{r_0 \cdot u^2}{4 \cdot d_{air\ gap}}$$

The relationship between the coefficient of friction, *f*, relative roughness and Reynolds number is usually presented in the form of a Moody diagram, which can be found in many works such as Schlichting (1978) and Olson (1980), to name a few. Alternatively, empirical correlations can be used. In these calculations, the value 0.055 has been used for all cases.

Measurements and calculations show that the Nusselt number is highest for the polystyrene pellets, followed by mineral wool and cellulose, see Figure 5. This indicates that the more permeable the material, the greater is the influence of air velocity on heat transfer in the material. If wind velocity above the insulation is as much as 1.5 m/s, which is reasonable in an attic space, heat losses can increase by 10 - 30% depending on the permeability of the material.

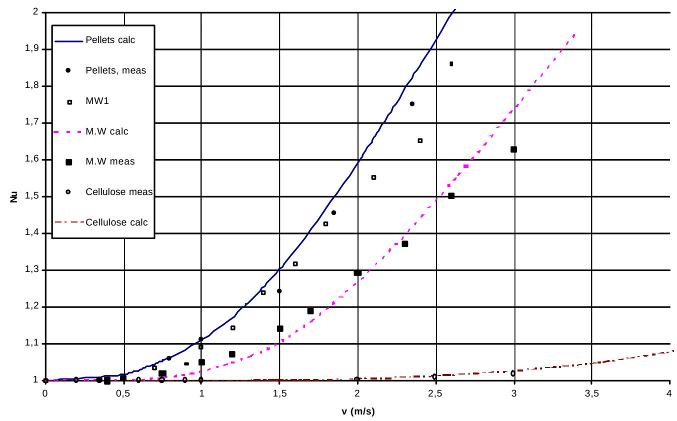

Figure 5. Nusselt Number as a function of air velocity in the air gap above the material. Comparison of calculations (line) and measurements (symbols).

5 PRACTICAL CONSEQUENCES

The thermal insulation performance of the attic floor depends on the choice of insulation material and the method of construction applied. In practice, workmanship and wind conditions around the building also affect this performance. An investigation performed by Silberstein et al (1991) showed that a wind velocity of ca 6 m/s outdoors can give rise to a wind velocity of ca 1.5 m/s parallel to the thermal insulation material in a ventilated attic; see Figure 6.

Investigations carried out by Bankvall (1978) and Nicolajsen (1989) have shown that heat losses steeply increase in a construction that has no wind protection. The pressure conditions to which the construction is exposed and which control airflows inside and around the construction are of the greatest interest for the thermal resistance of an insulated construction. Owing to their structure, loose fill insulations are more susceptible to external influences, such as wind effects, than solid insulation (slabs), mainly because they are installed without any form of wind protection whatever.

Hot box experiments performed by Taylor et al. (1983), indicate a 50% increase in heat losses when an air flow of at most 1 m/s was blown above the surface of 10 to 12 kg/m^3 glass fiber blanket.

The induced airflows, which can affect the thermal resistance of a construction, depend on the resistance to flow and pressure conditions. In places where there is a large pressure drop or where there is little resistance to flow, there is therefore a very high risk of airflows, which affect thermal resistance. Insulation materials of high permeability are protected from the wind-by-wind deflectors of low permeability.

When the construction is exposed to wind, most of the airflow is above the top of the insulation and parallel to this.

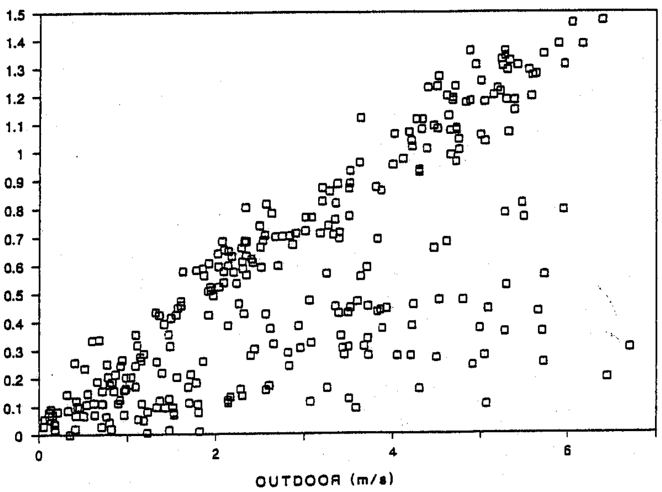

Figure 6. Air velocity in the cavity of a sloped roof (slope 22° – length 3 meters) against the outside wind velocity (Silberstein et al. 1991).

Since climatic conditions as regards wind and temperature vary over the year, assessments were also made of the influence of convection on energy use. Measurement results for mineral wool for both natural and forced convection, and climatic data for three different localities, Säve (southern Sweden), Bromma (central Sweden) and Luleå (northern Sweden), were used. Data for outdoor temperatures are based on hourly observations by the Swedish Meteorological and Hydrological Institute at these localities over a period of one year. In order that the influence of forced convection may be assessed, it was assumed, on the basis of a study made by Ann Silberstein et al (1991), that air velocity above the attic floor is 25% of the wind velocity outdoors.

For an attic floor of 100 m^2 area and insulation thickness of 0.5 m, calculations showed that natural convection has very little influence and that this is counteracted by the change in mean temperature when the outdoor temperature drops (the lower the mean temperature, the lower is thermal conductivity). On the other hand, forced convection may affect fabric losses from a 100-m^2 attic floor by as much as ca 10%. It should be pointed out that the calculations are based on a number of assumptions, which are debatable, such as insulation without any defects. At the same time, fabric losses through the roof are only part of the total losses. views of the practical implications of the results.

6 CONCLUSIONS

Comparisons with experimental results for natural and forced convection in a homogeneous horizontal insulation material show good agreement. Combining Darcy flow modeling with a surface resistance on the top of the material, representing insulation material in contact with an air layer, accurately predicts the heat flow through the system. Also the simple approximation with a linear pressure drop in the air layer, for the case of forced convection, was successful. 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 ($Ra_{m,c}$).

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, $Ra_{m,c} = 40$, to an open top surface in contact with an air space halves the critical modified Rayleigh number.

Both calculations and measurements show that the thermal insulation function of loose fill insulation may considerably deteriorate due to external factors such as wind action. In view of the Swedish climate and the materials which are at present used, natural convection has little influence on the thermal insulation capacity of the attic floor if the insulation has no defects. Research and development in this area is reflected in current building regulations; to sum up, satisfactory insulation function depends on

- properly thought out design as regards airtightness and protection against wind,
- the choice of insulation material of satisfactory performance as regards insulation capacity

and, in order that a satisfactory/expected performance may be achieved in practice, it is essential that

workmanship regarding placing, airtightness and protection against wind is satisfactory.

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