FORCED CONVECTION

PRACTICAL THERMAL CONDUCTIVITY IN AN INSULATED STRUCTURE UNDER THE INFLUENCE FROM WORKMANSHIP AND WIND

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Abstract

This paper describes the practical heat resistance in an insulated wall structure as influenced by workmanhip and forced convection. Experimental investigations on cross-bar walls are compared to calculations. Examples show the influence on heat resistance from insulation installation, air-flow along the insulation and air-flow through the insulation. Full information on theoretical calculations and experimental investigations can be found in (1).

Sammanfattning

Denna rapport beskriver värmeisoleringsförmågan i en väggkonstruktion under inverkan av arbetsutförande och påtvingad konvektion. Experimentella undersökningar på regelväggar har jämförts med beräkningar. Exempel visar inverkan på värmemotståndet av isoleringsutförande, luftflöde längs isoleringen och luftflöde genom isoleringen. Den fullständiga redovisningen av teoretiska beräkningar och experimentella undersökningar finns i (1).

Key words

Thermal insulation, permeability, forced convection, air leakage, workmanship.

Nyckelord

Värmeisoleringsförmåga, värmemotstånd, permeabilitet, luftgenomsläpplighet, påtvingad konvektion, lufttäthet, arbetsutförande.

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Nomenclature

A	area	(m^2)
B_o	permeability	(m^2)
B	permeans	(m)
d	thickness, diameter	(m)
L	length	(m)
p	pressure	(Pa)
R	thermal resistance	(m^2K/W)
Q	volume flow	(m^3/s)
v	velocity	(m/s)
λ	thermal conductance	(W/mK)
ρ	density	(kg/m^3)
η	viscosity	(Ns/m^2)

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The external wall of a building has as its primary function to preserve the desired indoor climate. Therefore, certain requirements are put on the different layers of the wall structure.

In principle the layers in a crossbar wall have the following function. The outside panel or brick wall protects against rain and direct wind. The air-space behind this enables ventilation of moisture. The wind protective sheet will secure insulation from external air movements. The insulating material gives the structure its main thermal resistance. The vapour barrier protects from moisture transport from inside and gives the wall its main air tightness. On the inside a board is mounted to facilitate the required surface treatment, for example with paint or wall paper. In this way the air tightness of the wall is normally further enhanced. Fig. 1.

The thermal resistance of the structure depends mainly on the insulating properties of the thermal insulation. In an actual structure the cold bridges from crossbars will increase the heat transfer. The thermal resistance observed in practice however, will also be influenced by workmanship and forced convection. The installation of the insulation will influence the final function. This is obvious, since often the thermal resistance of the insulating material is more than an order of magnitude greater than the resistance in the air-space which it fills. The effect is, however, poorly understood in quantitative terms. The

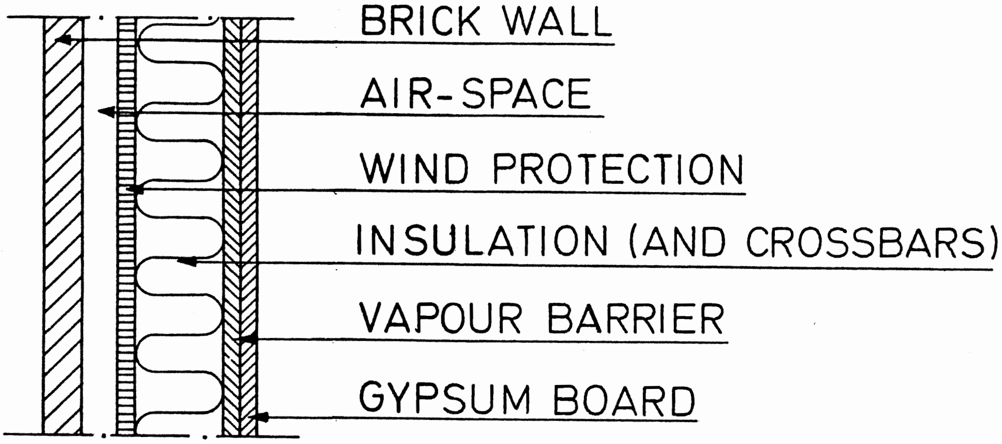

Fig 1 External multilayer wall

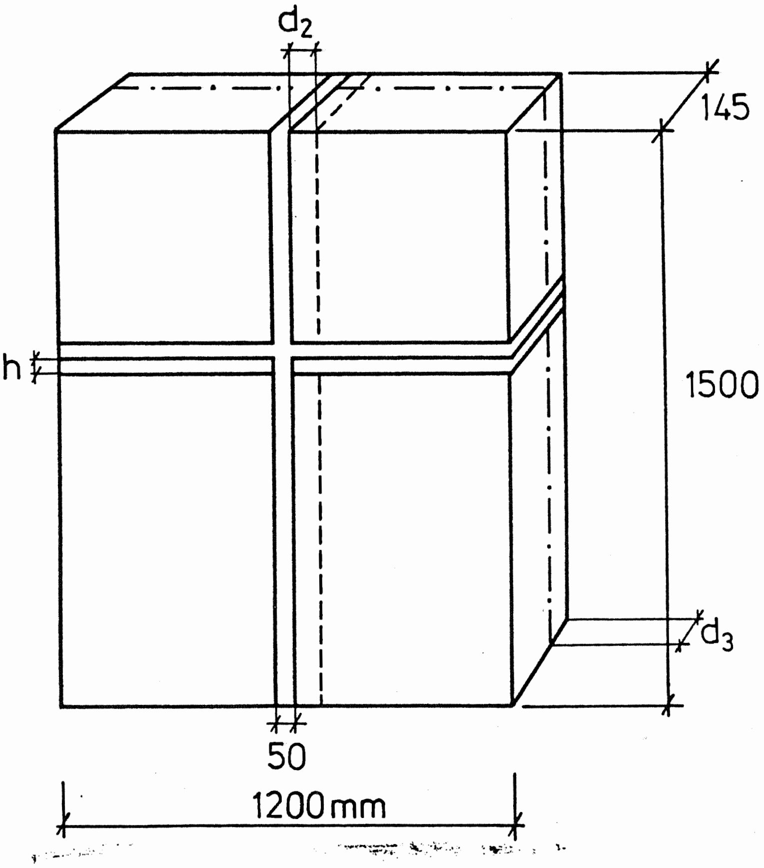

Fig 2 Crossbar test wall with example of insulation installation defects

h Horizontal "air-crack"

d_2 Vertical "air-crack"

d_3 Air-space, warm side

same is true for air movements due to forced convection. By forced convection is meant air movements governed from outside, for example by wind or mechanical ventilation. It is obvious that such air movements as well as those due to natural convection will influence the heat transfer in a structure or in a permeable insulating material.

Laboratory experiments

In order to investigate the effects of workmanship and forced convection investigations were made on a crossbar wall in the laboratory. The choice of wall structure and the actual test area being used were decided from field inventories, made at building yards. These field inventories showed what kind of workmanhip could normally be expected when the insulation was installed. Field measurements were also made to indicate what pressure differences could be found over e. g. the height or the thickness of a wall. These investigations gave information about how the laboratory experiments should be set up (1).

The test wall was mounted between two climatic chambers. One regulated to $+20^{\circ}C$ and the other to $-20^{\circ}C$. The pressure difference over the test wall could be controlled up to 20 Pa by evacuating the warm chamber somewhat.

The crossbar wall contained a test area which in its center had a cross of crossbars. Fig. 2. By having this cross in the test area various forms of insulation installation could be simulated within the area. This was achieved as indicated in the figure, which corresponds to defects recorded in practice.

The depth of the crossbar space was 0.145 m. On the inside of the insulation was a plastic foil and a gypsum board. On the outside different types of wind protection were mounted. Outside this wind protection there was an air-space where the air-flow could be regulated. The thermal resistance values found in this way were from analyses and calibration measurements estimated to have an accuracy better than 8 %. (1).

The insulating materials used in the experiments were chosen with regard to their permeability. The thermal conductance values were approximately identical. The aim was to investigate to what extent air movements, either in built-in air-spaces around the insulation or due to forced convection from outside, would influence the heat transfer in the insulation itself. The materials under investigation are listed together with measured parameters

	ρ (kg/m^3)	B_o (m^2)	λ (W/mK) (at 0°C)
glassfiber	16	$40 \cdot 10^{-10}$	0.034
rockwool	40	$20 \cdot 10^{-10}$	0.0335
cellular plastic	20		0.033

In one part of the investigations measurements were performed with different kinds of wind protection. In this case too the wind protection materials were chosen with regard to their permeance since this is the most important factor when evaluating the influence from forced convection. The wind protection materials were mainly the following.

	d(m)	B(m)	λ (W/mK) (at $0^{o}C$)
asphaltimpregnated porous fiberboard	0.013	$3.8 \cdot 10^{-10}$	0.07
mineralwool board	0.03	$150 \cdot 10^{-10}$	0.03

Workmanship

In practice the thermal resistance of a crossbar wall will depend upon the workmanship when installing the insulation. Field investigations have shown that deficient workmanship generally leads to that the insulation insufficiently fills the space to be insulated, i.e. the material is cut or mounted so that air-spaces or cracks are formed around the insulation (1). Generally two main kinds of air-spaces are noted. 1) "The crack" is an air-space going through the insulation from the warm to the cold side, 2) "the space" is an air-space on one side of the insulation either the warm or the cold side (c.f. fig. 2). To study the influence of spaces or cracks on the heat transfer, measurements were made on the test wall carrying such defects. These measurements were then compared with theoretical calculations.

The heat transfer coefficient in air cracks or in air-spaces was evaluated theoretically by calculation of the convective and the radiative heat transfer. The result from one such calculation is shown in fig. 3, giving the heat transfer coefficient for a vertical crack of varying width as a function of insulation thickness.

Fig. 4 shows the results from measurements on the test wall with vertical cracks in the insulated space. The figure indicates fair agreement between the measured values and the calculated curve. This was also true with the other mineralwool insulation. However, in case of the cellular plastic, consistently lower values were measured as compared to theoretical predictions. This was attributed to the diffi-

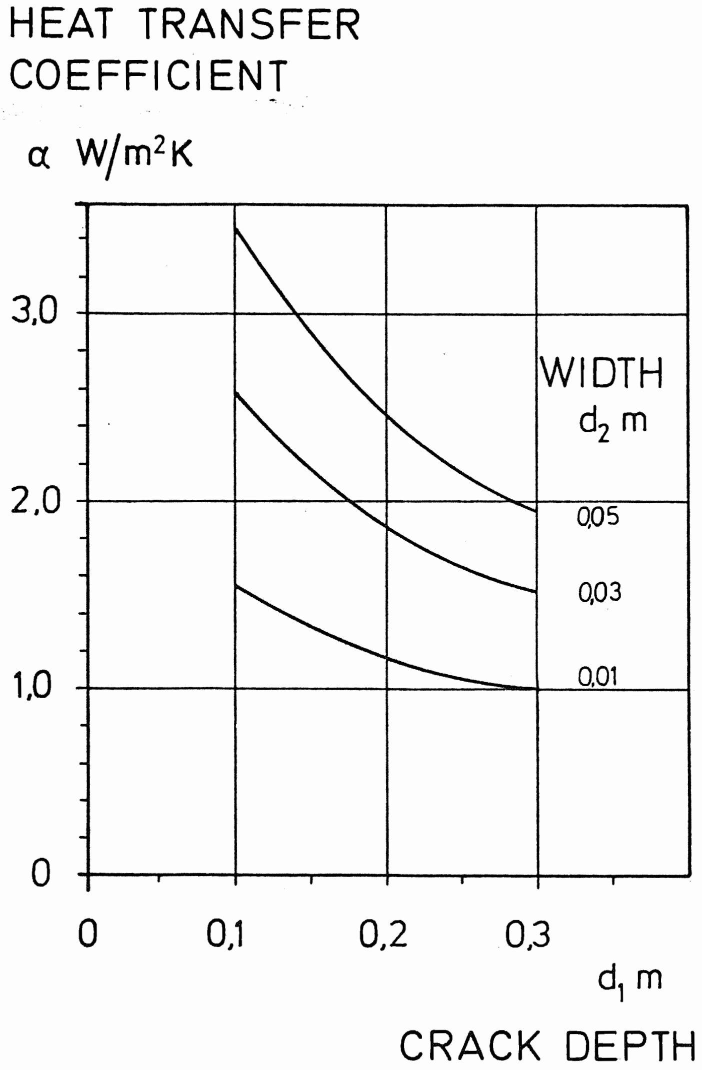

Fig 3 Calculated heat transfer coefficient for vertical air-crack (width d_2, depth d_1, $T_m \approx 0^{\circ}C$, $\Delta T \approx 35^{\circ}C$).

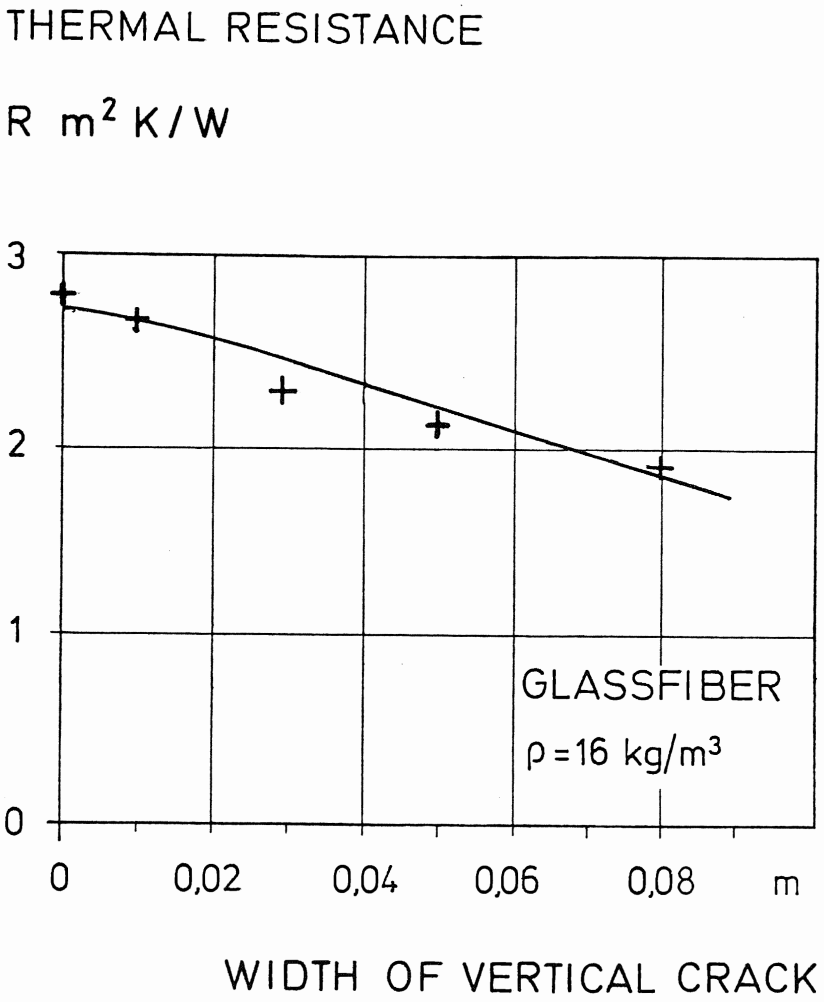

Fig 4 Reduction of thermal resistance due to vertical crack in insulated space of test wall (cf. fig. 2). Comparison between measured values and calculated curve.

culty in completely filling the insulated space with this insulation which had a very low compressibility. The material had to be cut with height and width 5 mm less than the space to be insulated to make installation possible.

Measurements on horizontal cracks and on air-spaces in the insulated space showed similar results. All measurements were performed in absence of any influence of forced convection on the structure.

Comparisons between the theoretical analysis and the laboratory measurements indicate that the theoretical model could be used to illustrate the influential factors. A representative example is given in fig. 5, which shows the dominant effect on the thermal resistance value from vertical air crack in an insulated crossbar space. The figure reveals that the higher the thermal resistance the greater the influence from air cracks. This example also shows that the important factor is the extent to which the insulating material fills the space to be insulated. The measurements also demonstrated that the permeabilities of the different insulation materials used in this study were of no importance to the overall thermal resistance of the wall (1).

Forced convection

The heat transfer in a structure can be affected by forced convective air-flow. Factors governing this flow are the pressures around the structure and the flow resistances in the materials and the joints between materials.

Two different kinds of forced convection can be considered in principle. One is air-flow through an insulated structure, the other is air-flow along an insulated structure. Fig. 6.

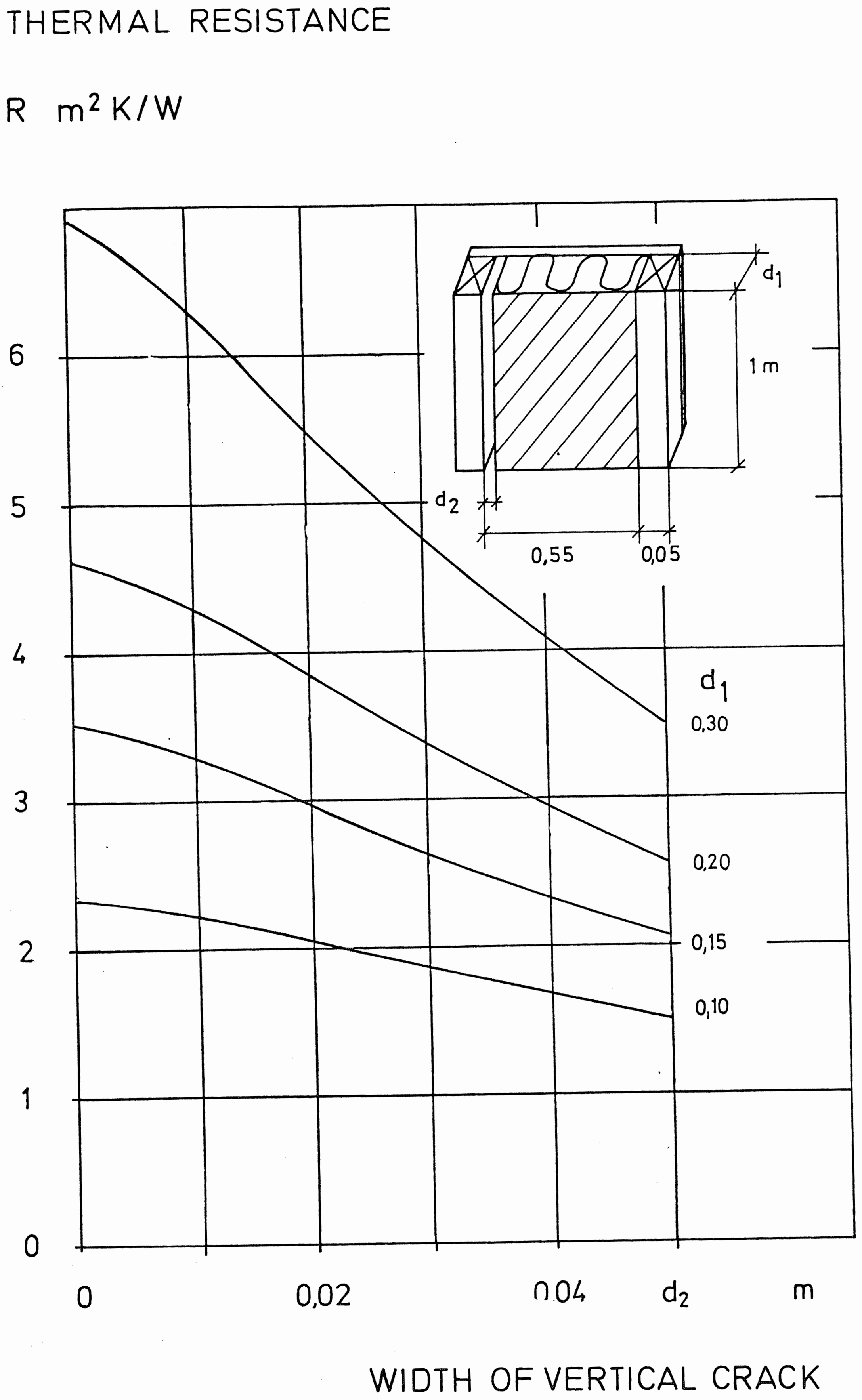

Fig 5 Reduction of thermal resistance in crossbar wall due to vertical crack in insulated space with varying insulation thickness. λ (insulation) = 0.035 W/mK.

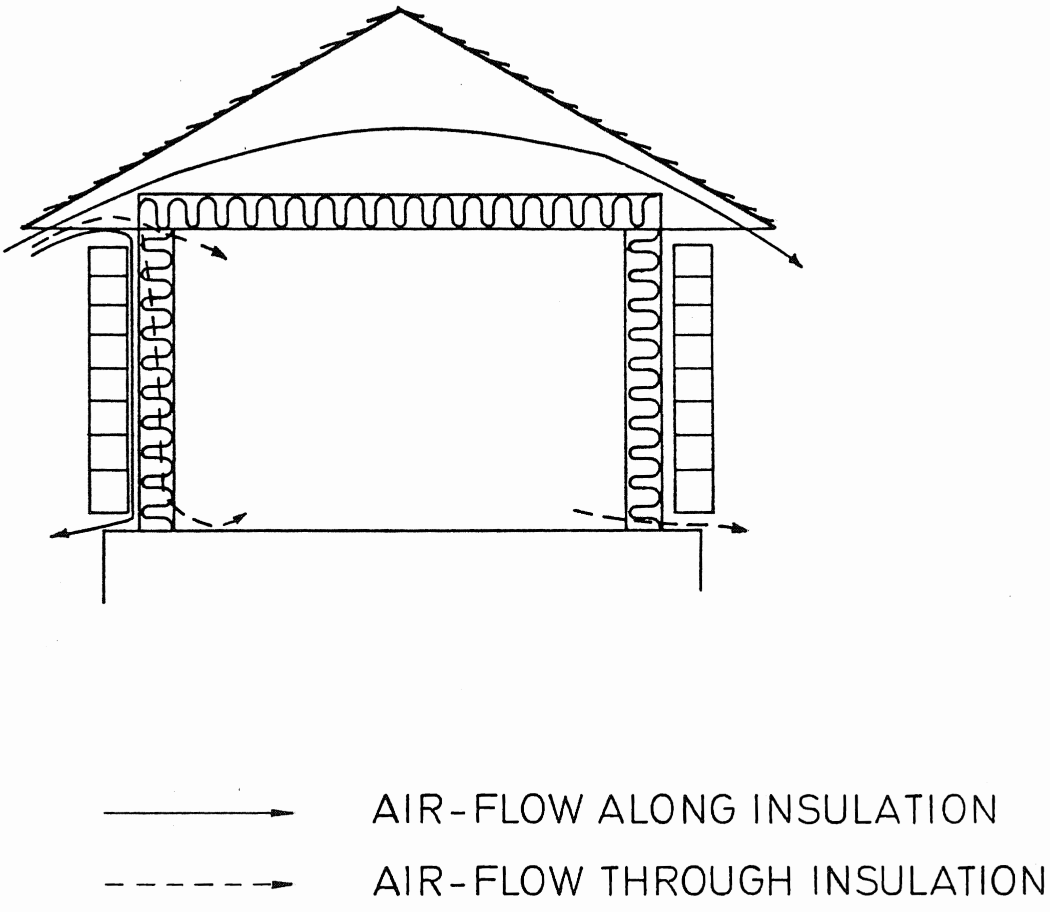

Fig 6 Principle types of forced convective influence on thermal insulation.

In the first case the air-flow is mainly from warm to cold side at right angle to the wall layers. In the second case the air-flow is mainly along the layers, eventually passing sections of the insulation without going from warm to cold side. The two types of forced convection are defined separate, however in practice intermediate types are common.

To calculate air-flow due to forced convection the following equations were used.

In the case of turbulent air-flow the equations for pipe-flow were used.

$$\frac{\Delta p}{\Delta x} = \beta \cdot \rho \cdot \frac{v^2}{2\ d_R}$$

where β is a friction factor indicated in diagrams (1). Δp is the pressure difference, Δx the flow length, ρ the density, v the velocity and d_R the pipe diameter.

In cases of bends, elbows, contraction or expansion in the pipeline, the following equation was used

$$\Delta p = \xi \cdot \rho \cdot \frac{v^2}{2}$$

where ξ defines a loss coefficient (1).

The above equations are true for circular cross sections. For other cross sections approximate calculations were made by using the hydraulic diameter.

$$d_H = \frac{4\ A}{S}$$

where A is the area and S the perimeter of flow.

For laminary flow in an air-space or in a crack the following equation was used

$$\frac{\Delta p}{\Delta x} = 12\ \eta\ \frac{v}{b^2}$$

where b is the crack width and η the viscosity.

Air-flow through cracks can be calculated in principle from the previous equations. This, however, presupposes a detailed knowledge of the flow path and its dimensions and surface properties. In many cases, therefore, empirical equations of the general type expressed below are used.

$$Q = v \cdot A = \alpha \cdot \Delta p^{\gamma}$$

where α and γ are derived from measurements and vary with different structures. $\gamma = 1/2$ indicates that the flow is turbulent, $\gamma = 1$ indicates that it is laminar. Q denotes the volume flow (m^3/s).

For calculation of flow through openings in thin layers the following equation was used (2)

$$Q = 0.827 \cdot A \cdot \Delta p^{1/2}$$

Flow through joints, in for example, wind protection sheets was evaluated by the following equation derived from measurement (3)

$$Q = 0.28 \cdot 10^{-5} \cdot L \cdot \Delta p^{0.75}$$

for a nailing distance of 100 mm. L denotes the length of the joint.

For overlapping and clamped joints in vapour barriers measurements yielded the following equation (4)

$$Q = 2 \cdot 10^{-7} \cdot L \cdot \Delta p$$

For flow through permeable material the equation used was

$$Q = \frac{B_o}{\eta} A \frac{\Delta p}{\Delta x}$$

This equation is only valid for laminar flow, i.e. at moderate flow velocities, higher velocities require corresponding measurements, giving permeability (B_o) that varies with velocity.

The flow characteristic of a layer can also be described by its permeans B

$$B = B_o/d$$

Air-flow along insulation

Air-flow along an insulation can be illustrated as in fig. 7. The figure shows an outer wall consisting of a brick-wall, an air-space, wind protection and insulated cross-bar space. The ventilation in the air-space is facilitated by openings over and at the bottom part of the brick-wall. In some cases the permeability of the brick-wall may contribute to the ventilation of the air-space.

Depending upon the pressure difference in the air-space and the wind protection there may exist an interchange of air between the air-space and the insulation. This interchange varies over the height of the insulated space. The

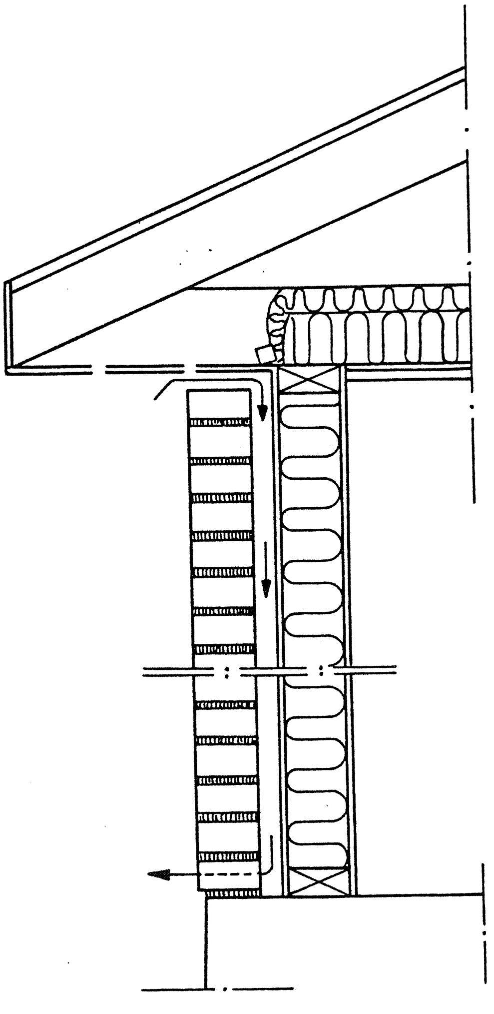

Fig 7 Air-flow in air-space along insulated crossbar structure with outer brick wall.

results of calculation for an insulated space with height and width 1 m are shown in fig. 8. The pressure over the height of the space was 5 Pa. The insulating material had a specific permeability of $B_o = 40 \cdot 10^{-10}$ m^2. The insulation thickness was 10 cm. In fig. 9 the air interchange between the air-space and the insulation has been considerably reduced by a wind protection of asphalt-impregnated porous fiberboard. The calculations were based on the previously presented equations.

To establish the influence of this type of air-flow on the thermal resistance of the insulated space experiments were conducted with the crossbar wall. The forced convection was simulated by regulating an air-flow along the wall on the cold side. The air-flow velocity was 2.5 m/s, corresponding to a pressure gradient of 0.7 Pa/m. Comparisons were made with fully insulated walls, wind-protected in different ways. Fig. 10. The reduction in thermal resistance due to the forced convective flow was less than 10 %, even for the unprotected insulation. The measured values are also in fair agreement with calculations.

Measurements were also carried out on the crossbar wall with defects in its insulation installation. Fig. 11 shows the reduction in thermal resistance for the crossbar wall with vertical cracks under the influence of forced convection. When the wall was unprotected and exposed to full forced convection air-flow velocity ≃ 2.5 m/s (2.5) there was a substantial decrease in thermal resistance. Also with reduced forced convection air-flow velocity ≃ 0.1 m/s (0) the decrease was noticeable. If, on the other hand, the structure was protected by an asphalt-impregnated porous board the reduction in thermal resistance was substantially reduced. Measurements on other insulations showed approximately the same results (1).

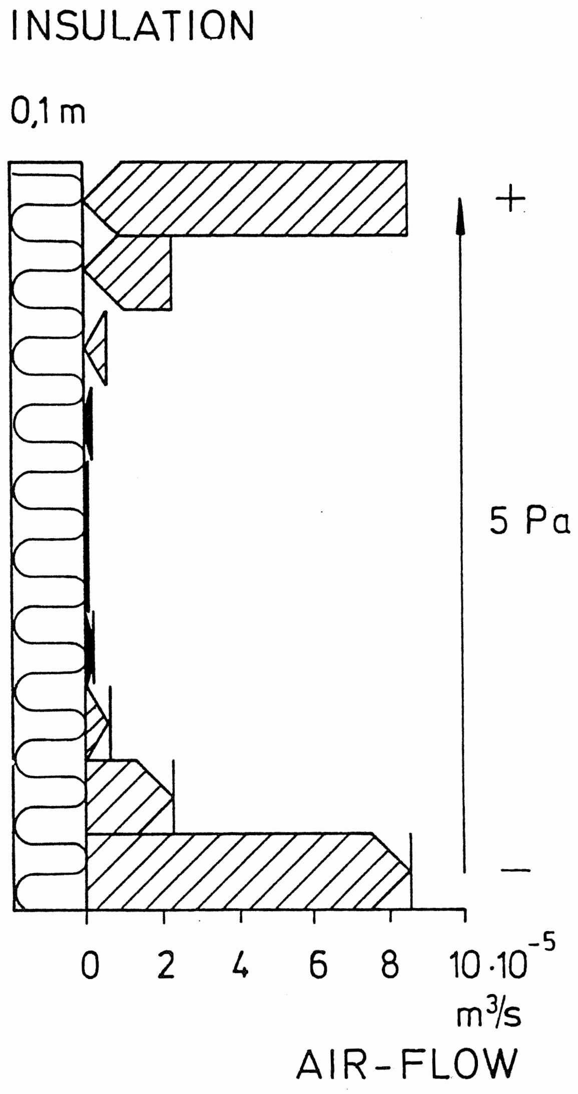

Fig 8 Air interchange between insulation and air-space with air-flow along the insulated space (cf. fig. 7). Insulation thickness 0.1 m, height 1 m, B_o = $40 \cdot 10^{-10}$ m^2. Pressure difference over height 5 Pa/m. Unprotected insulation.

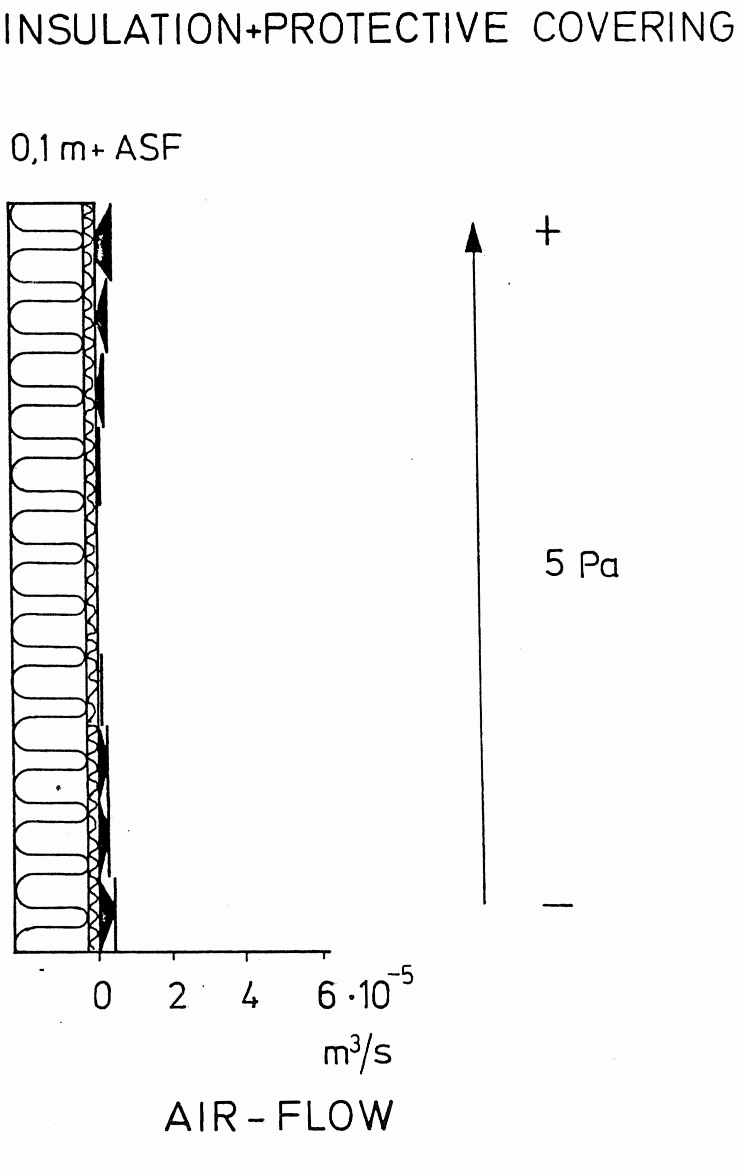

Fig 9 Air interchange between insulation and air-space with air-flow along the insulated space (cf. fig. 7). Insulation thickness 0.1 m, height 1 m, B_o = 40 · 10^{-10} m^2. Pressure difference over height 5 Pa/m. Wind protection by asphalt-impregnated board (ASF, B = 3.8 · 10^{-10} m.)

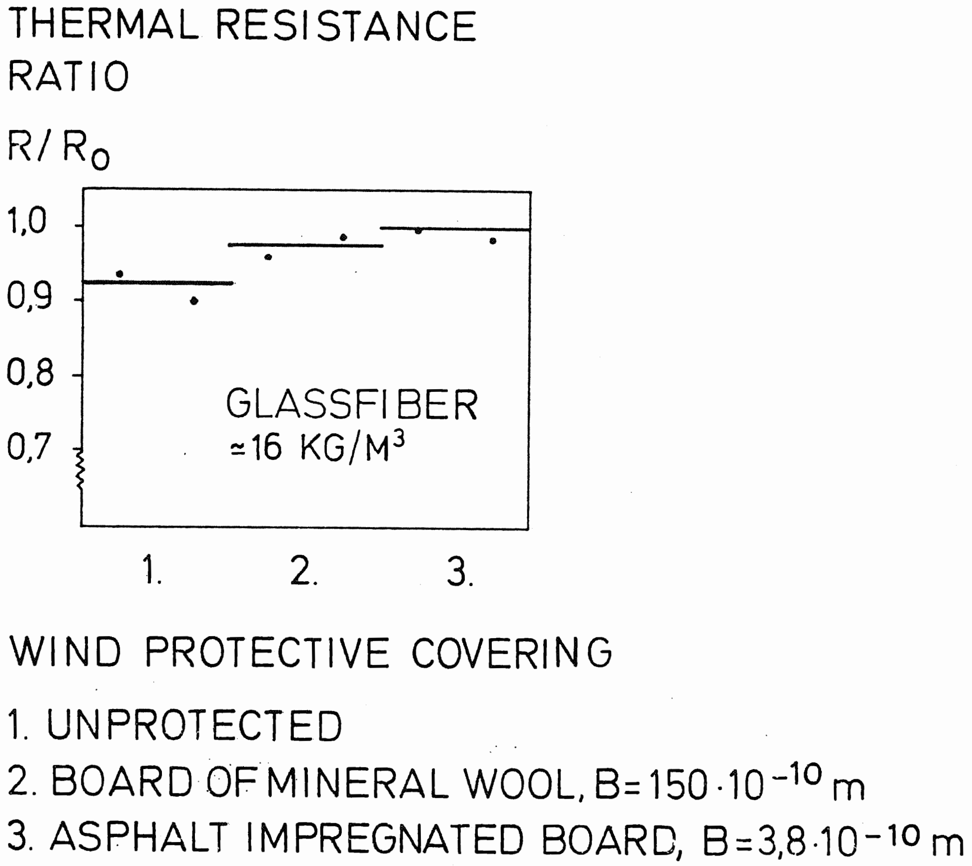

Fig 10 Reduction in thermal resistance of crossbar wall. Insulation thickness 0.15 m. Pressure difference over height of test wall 0.7 Pa/m. Comparison between measured values and calculated levels.

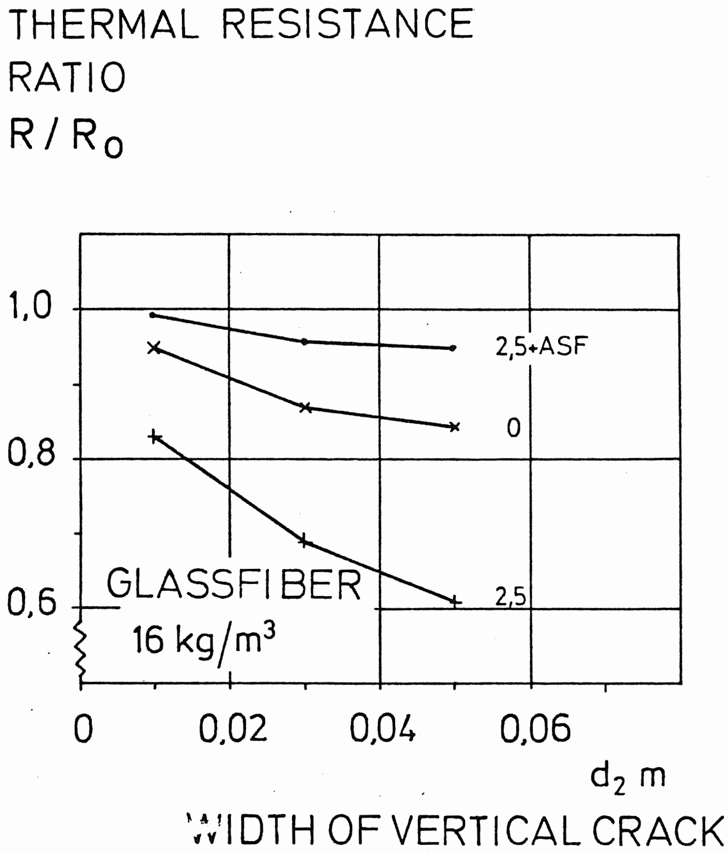

Fig 11 Reduction in thermal resistance of crossbar test wall with vertical crack and varying wind protective covering $B = 3.8 \cdot 10^{-10}$ m and air-flow along the insulated space.

ASF: Protected by asphalt-impregnated board
2.5: 2.5 m/s (≃ 0.7 Pa/m)
0 : 0.1 m/s

In conclusion these measurements indicated that for a well windprotected and installed insulation there was little influence from the permeability of the insulating material. At high loads of forced convection the unprotected structure showed a larger reduction in thermal resistance when the permeability of the insulating material increased. This applied especially in the case with defects in the insulation installation. Wind protective covering with high permeance gave a slightly higher reduction in heat resistance, especially if high permeance was combined with high permeability in the insulating material. The influence from air-flow along the insulation when installation defects were present in the insulated space are illustrated by the experimental investigations.

The heat transfer in the fully insulated wall can be calculated theoretically as well. This is shown in fig. 12 where thermal resistance for an insulated structure is given as a function of pressure difference over the height of the insulated space, thermal insulation thickness and different wind protective covering with varying thermal resistance and permeance. The insulated structure with high thermal resistance is more sensitive to this kind of forced convection. This structure will also require a wind protection with low permeance. The figure also shows how the mineralwool board initially increases the thermal resistance of the structure. This increase is gradually lost when the forced convection increases.

Air flow through insulation

Air-flow through an insulated crossbar wall is examplified in fig. 13. The air-flow from the outside passes mainly through openings at the top and bottom of the brick wall and only partly through the wall itself. The main cross-

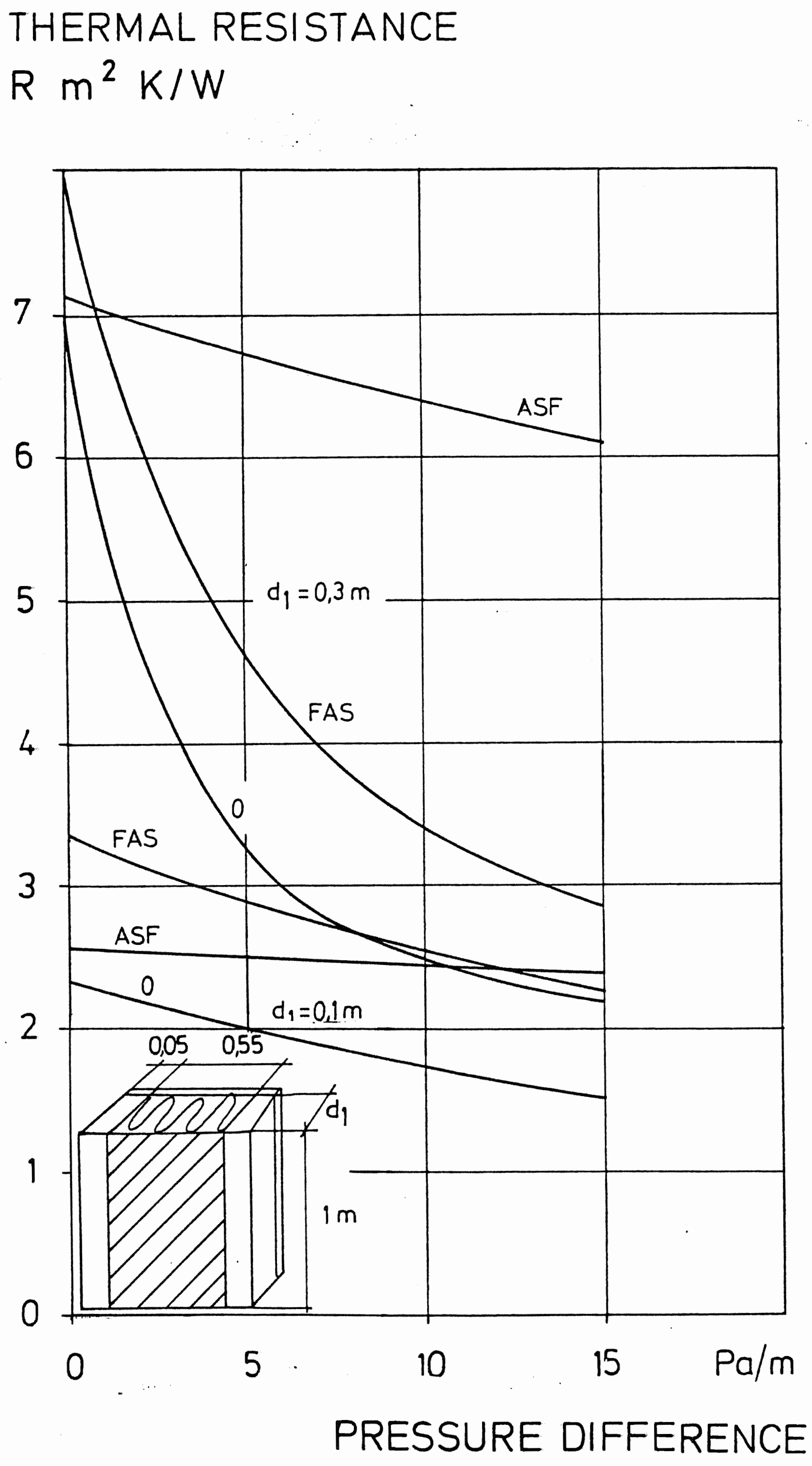

Fig 12 Reduction in thermal resistance of crossbar wall due to flow along the insulated space. Insulation, $B_o = 40 \cdot 10^{-10}$ m^2 and $\lambda = 0.035$ W/mK

Wind protective covering:

ASF: Asphalt-impregnated board, $B = 3.8 \cdot 10^{-10}$ m

FAS: Mineral wool board, 0.03 m, $B = 150 \cdot 10^{-10}$ m

O : Unprotected

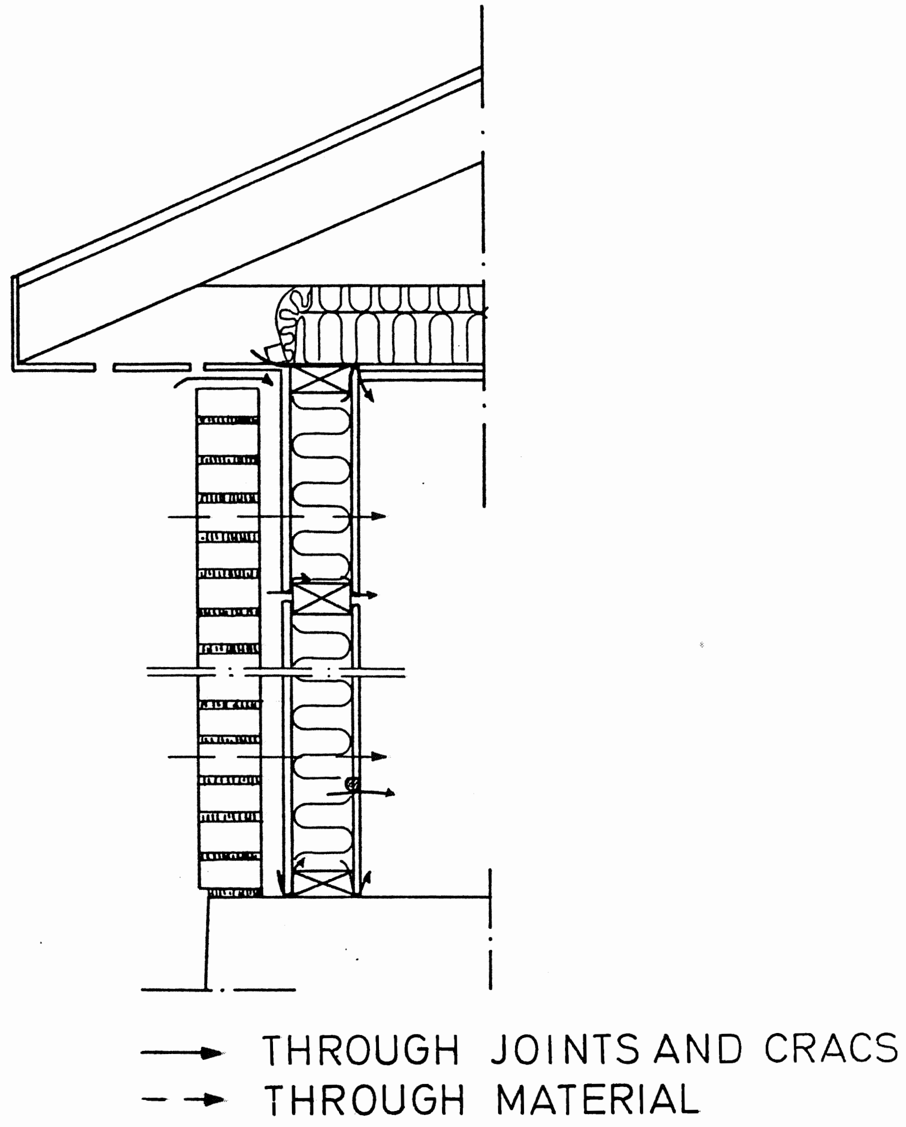

Fig 13 Principal ways of air-flow through insulated cross-bar structure with air-space and outer brick wall.

bar part of the wall has a wind protection on the outside and a vapour barrier and a board on the inside. Through this part of the wall the air will flow through the materials themselves and through the joints between materials in the different layers. The inside board and its vapour barrier constitutes the main protection against air-flow through the wall. For these layers joints between materials and small air-cracks for example round electrical installations may be of great importance with regards to the air tightness of the wall (1).

The air-flow through the wall can be calculated from the equations presented previously. In each layer the flow resistance of the material itself, of joints between materials and of eventual holes have to be considered.

The effect of air-flow on the thermal resistance through the crossbar wall was investigated in the test situation presented previously. To study the influence from air-flow through the insulation, holes were made in the inside board and the vapour barrier. (Hole area in vapour barrier $A = 2.36 \cdot 10^{-4}\ m^2$, in inside board $A = 4.55 \cdot 10^{-4}\ m^2$). Measurements were made with various thermal insulations with different wind protections. In some measurements half the number of holes in the inside gypsym board were covered by tape. Results from the measurements are shown in fig. 14. The measured values indicate a lesser reduction in the heat resistance value than the theoretically calculated curve. The difference, however, is well within the accuracy of determining the hole area in reality. Therefore these observations can be accepted as in sufficient agreement with theory. The results were similar for all the different kinds of insulations.

Using the previous equations calculations were made of the thermal resistance of a typical insulated crossbar space. Fig. 15 shows the decrease in thermal resistance for two

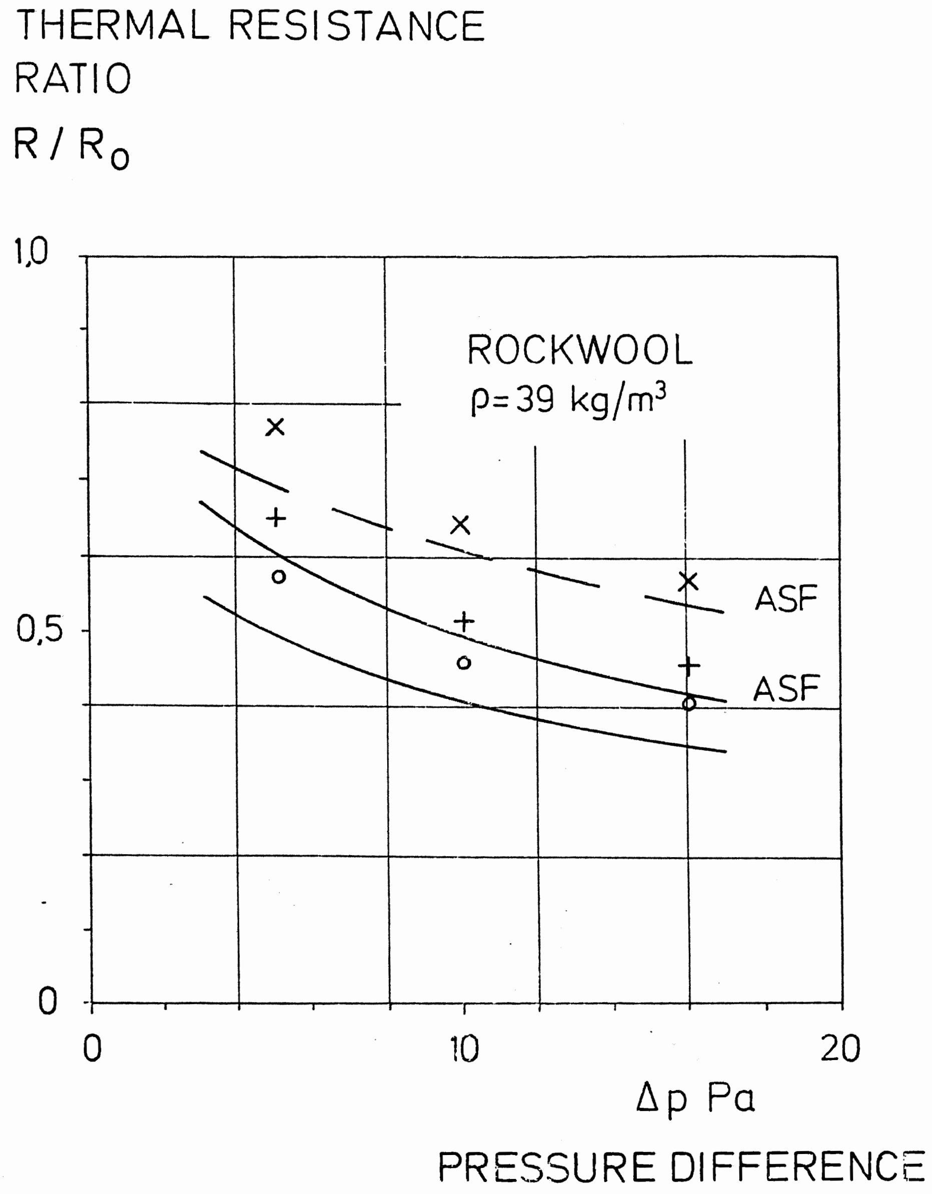

Fig 14 Reduction in thermal resistance due to air-flow through the insulated crossbar test wall. With and without windprotection by asphalt-impregnated board. Holes through the gypsum board and the vapour barrier according to the text (+,o), half the holes in the gypsum board covered by tape (x).

ASF: wind protection by asphalt-impregnated board

$$B = 3.8 \cdot 10^{-10} \text{ m}$$

Otherways unprotected

Comparison between measured values and calculated curves.

insulation thicknesses and two different cases, one with vapour barrier, the other without. The results shown are obtained with different kinds of wind protection. The influence from the wind protection is mainly two-fold. One is the enhanced thermal resistance and the other is the increase in total resistance to air-flow through the structure.

In summary, to prevent air-flow through the insulated structure the air tightness of the vapour barrier and partly of the inside board is of great importance. If there are holes and defects in these layers the permeance of the wind protection can be of importance to the overall air-flow through and the heat resistance of the wall. An insulated wall structure with such defects will however normally show a considerable reduction in its thermal resistance due to forced convective air-flow.

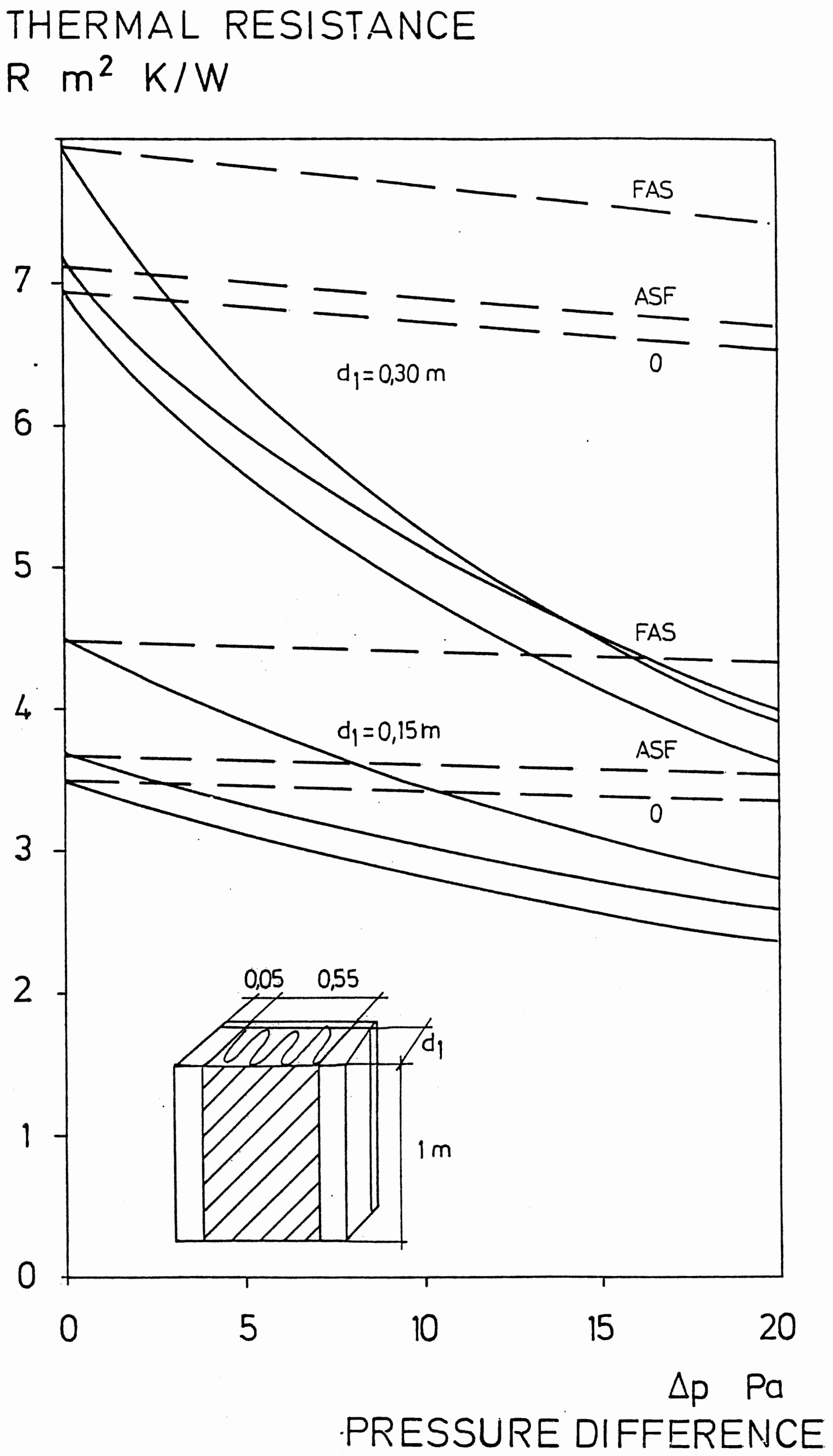

Fig 15 Reduction in therjal resistance due to air-flow through the insulation and with (---) and without (——) vapour barrier. Insulation thickness d_1 m
λ (insulation) 0.035 W/mK

Wind protective covering:

ASF: Asphalt-impregnated board, $B = 3.8 \cdot 10^{-10}$ m

FAS: Mineral wool board, 0.03 m, $B = 150 \cdot 10^{-10}$ m

O : Unprotected