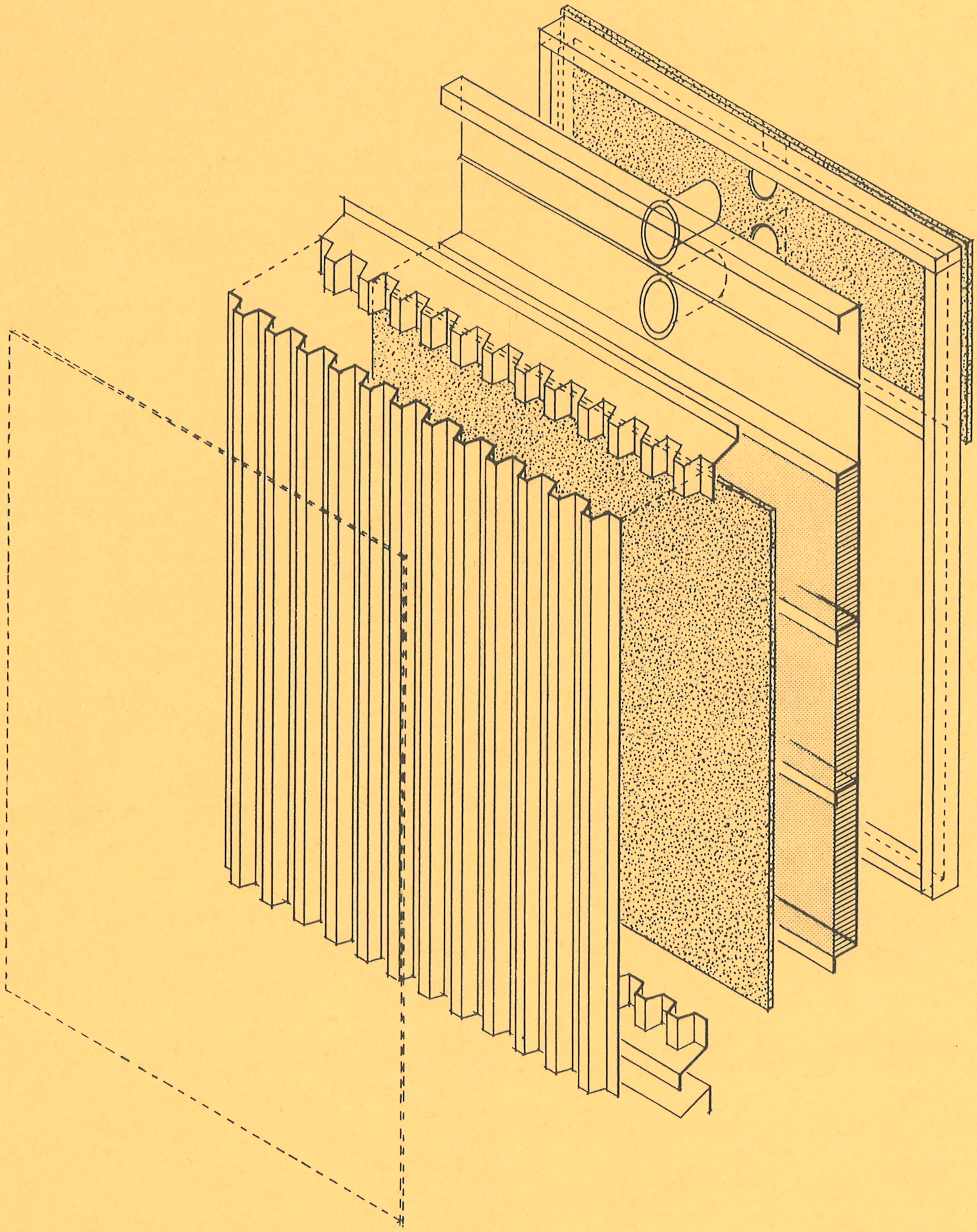
THERMAL INSULATION LABORATORY - TECHNICAL UNIVERSITY OF DENMARK



Results from tests on a Multi-Function Solar Energy Panel

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Preface

The present report describes the experience from tests carried out on two prototypes of a Multi-Function Solar Energy Panel. On the basis of these tests, simulations have been performed in order to establish knowledge of the annual performance of such a panel under different operational conditions.

The report is the conclusion of a project financed by the Danish Ministry of Energy with the title "Façade panel for energy gain" - SBI journal no. 1213-702-05-01 under EFP87 (the Energy R & D programme 1987 of the Danish Ministry of Energy).

The work within the project has been made as a cooperation between the Thermal Insulation Laboratory (Thecnical University of Denmark), the Architects Arne Meldgaard and Techline International Energy Systems.

Summary

The present report deals with the experience and conclusions gained from tests carried out on two prototypes of a Multi-Function Solar Energy Panel (MF-panel). Besides being the wall (or the roof) of a house the panels investigated in this project may both serve as an air based solar collector for direct heat injection to the house and as a heat exchanger between fresh air to the house and exhaust air from the house. The panel has, furthermore, a smaller heat loss to the surroundings than a normal wall (or roof).

The efficiency of the two MF-panels, that operate only as solar collectors or only as heat exchangers, has been measured for different flows through the panel. On the basis of the measured efficiencies, simulations have been performed to establish knowledge of the annual performance of such panels mounted in a house under different operational conditions - tilt, orientation and air flow through the panel.

Some preliminary investigations have further been performed in order to find theoretical equations for calculation of the efficiency of the MF-panel used as solar collector and heat exchanger, to find the influence of condensation in the MF-panel and to find the reduction of the heat loss compared to a normal wall.

Resumé

Nærværende rapport beskriver erfaringer og konklusioner fra forsøg udført med to prototyper af et Multi Funktions Facade Element (MF-element). Ud over at være væggen (eller taget) fungerer de i projektet undersøgte elementer både som en luftsolfanger med direkte varmeindblæsning til huset og som varmeveksler mellem friskluft til og afkastluft fra huset. Elementet har desuden et mindre varmetab til omgivelserne end en normal væg (eller tag).

Effektiviteten af de to MF-elementer som ren solfanger og ren varmeveksler er blevet målt ved forskellige volumenstrømme gennem elementet. På basis af de målte effektiviteter er der foretaget simuleringer for at skabe kendskab til det årlige udbytte af et MF-element installeret i et hus under forskellige driftbetingelser - orientering, hældning og volumenstrøm gennem elementet.

Indledende undersøgelser er desuden udført for at finde teoretiske udtryk til beskrivelse af MF-elementets effektivitet som kombineret solfanger og varmeveksler, for at finde indflydelsen af kondensation i MF-elementet, samt for at finde reduktionen i varmetabet sammenlignet med en normal væg.

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1 Introduction

A Multi-Function solar energy panel - in the following abbreviated to MF-panel - is constructed to adapt a facade often used for industrial buildings, a facade with corrugated metal profiles serving several different energy purposes.

The outer part of the panel consists of a flat plate - either a metal sheet or a transparent plate - behind this plate there is a metal sheet with a trapezium corrugated profile. The two plates are mounted in front of a normally insulated outer wall. At the top (and maybe at the bottom) of the panel there are box-shaped manifolds - see fig. 1.1. In this way it is possible to let in air through the manifolds into the two sets of air gaps formed by the trapezium corrugated metal sheet. In this way the panel can act both as a solar collector and as a heat exchanger between fresh air to the house and exhaust air from the house. If the exhaust air is led down between the insulated wall and the trapezium shaped plate the heat loss through the wall will furthermore be reduced, as the temperature will be higher on the outside of the insulated wall during the heating season than the ambient air temperature.

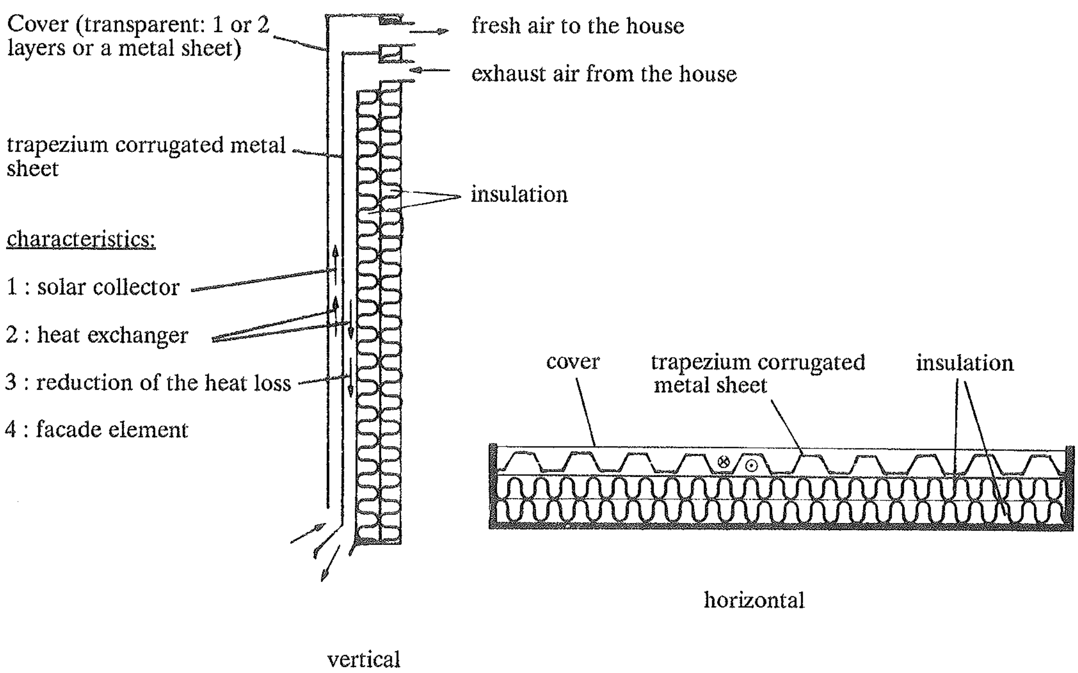

Figure 1.1 Outline of one of the applications of a Multi-Function solar energy panel (MF-panel).

1.1 Applications for MF-panels

The MF-panel can serve different purposes:

1) Solar collector,
2) Solar collector and heat exchanger for preheating of fresh air,
3) Preheating of air to the condenser of a heat pump.

1.1.1 The MF-panel as solar collector

The MF-panel can be used as solar collector both for heating of domestic hot water and for space heating.

When used for heating of domestic hot water the air temperature has to be at least 50 °C in order to use the water directly. For lower air temperatures the water can only be pre-heated. An air to water heat exchanger is necessary in order to transfer the heat.

When used for space heating the hot air can either be supplied to the house directly or indirectly through a storage. A system with a storage will have the best performance.

Both the above mentioned cases demand that the solar collector (different from fig. 1.1) forms a closed circuit with limited air leakages in order to achieve sufficiently high temperatures.

1.1.2 The MF-panel as solar collector and heat exchanger for preheating of fresh air

This case is shown in fig. 1.1. The MF-panel here consists of two separate duct systems with a large common wall, which is very suitable for heat exchange between the fresh air to the house and the exhaust air from the house. The system will furthermore benefit from the solar radiation on the panel.

1.1.3 The MF-panel in connection with a heat pump

When the air to the condenser of a heat pump is heated to a temperature higher than the ambient temperature the efficiency of the heat pump will be increaseed.

1.2 Present work

The work reported here has mainly been to deal with the MF-panel used as a solar collector and a heat exchanger for preheating of fresh air, as it was felt that the greatest novelty value was within this area. It is also estimated in a previous project (Olsen, 1986) that it is within this area that the MF-panel will have the best performance. Some of the conclusions obtained from the work can, however, also be used in connection with other applications of the MF-panel.

The report presents tests carried out on two prototypes of MF-panels - one panel with a transparent cover and one with a cover of black painted steel. The efficiency of the MF-panels acting purely as a solar collector and purely as a heat exchanger has been measured depending on the air flow through the panel. Stagnation temperatures for the panel acting as solar collector, and the pressure drop across the MF-panel have been measured. Preliminary investigations have been made in connection with condensation in the MF-panel and the reduction of the heat loss through the insulated wall and an evaluation is given of how to describe the panel theoretically. Finally simulations have been carried out in order to find the annual performance of a MF-panel mounted on a house.

The MF-panel design is a new concept, it has, therefore, not been possible to make a thorough investigation within the framework of the present project. The work has been concentrated on obtaining knowledge of the efficiency of MF-panels acting as solar collectors and as heat exchangers and by simulations to investigate the probable annual performance of MF-panels installed in a house. Other aspects have been covered briefly in order to give an impression of the influence of these mechanisms on the performance of the MF-panel.

2 Background

The aim of this chapter is to describe some basic thermal processes occurring in a MF-panel in order to make it easier for the reader to understand the structure of the prototypes of the MF-panels developed within this project.

In the evaluation of the performance of the MF-panel it is necessary to distinguish between two fundamentally different designs of the MF-panel:

1) The outer cover of the panel is a metal sheet,
2) The outer cover of the panel is transparent.

The heat transmission between the two air flows is the same in both cases when the MF-panel works only as a heat exchanger, but the collection of solar radiation is highly dependent on the type of cover.

2.1 Metal sheet as outer cover

When the outer cover is a metal sheet, the absorption of solar radiation takes place on the outside of the metal sheet. The amount of absorbed solar radiation depends on the absorption coefficient of the surface. A dark mat colour will typically have an absorption coefficient of 0.9-0.95, while a bright surface will reflect most of the solar radiation.

A major part of the absorbed solar radiation is lost to the surroundings due to convection (mainly caused by wind) and radiation, while the rest is conducted through the metal sheet and transferred to the air behind the sheet via convection and to the opposite wall via radiation.

Figure 2.1 gives an impression of the efficiency of solar collector without a cover in front of the absorber. The figure shows the efficiency of a collector used for heating of swimming pools. In this collector the fluid inside the absorber is water - not air. The heat exchange between the absorber and the fluid is highest when the fluid is water, this means that the MF-element will have a somewhat lower efficiency than shown in figure 2.1.

The figure shows, that the performance is very low when the temperature of the absorber exceeds 10 °C.

2.2 Transparent outer cover

By means of a transparent cover the solar irradiance is transmitted through the cover before it hits the absorber. The efficiency of this type of collector depends, therefore, both on the optical properties of the cover and the surface properties of the absorber.

The cover may consist of a single layer of glass or acrylic or of several layers of plastic - acrylic or polycarbonate. The optical loss through a single cover lies between 10 and 20% (Østergaard Jensen, 1986a) while, as an example, the reduction is 16% when a double walled polycarbonate plate is used. More layers will reduce the transmission even more.

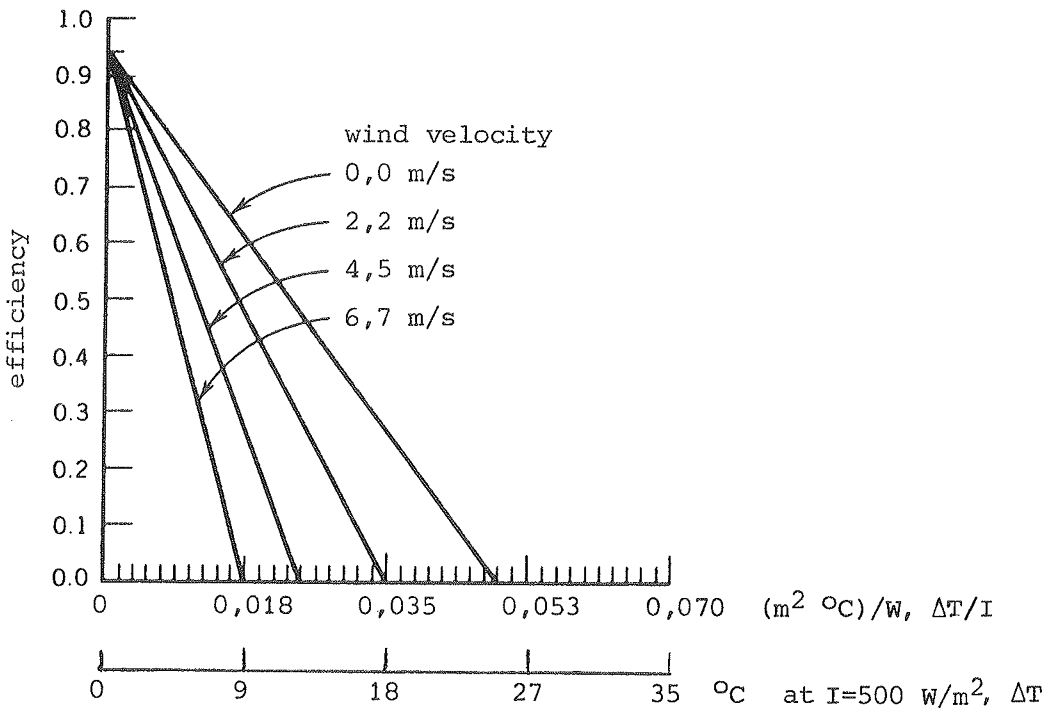

Figure 2.1 Efficiency curves for a solar collector without cover in front of the absorber. The efficiency is shown for four different wind speeds along the absorber. The efficiency is here shown as a function of ΔT/I, where ΔT is the temperature difference between the absorber and the ambient air [°C], and I is the solar radiation [W/m2]. ΔT is further shown for I=500 W/m^2 (Harris et al, 1985).

The advantage of having a transparent cover is, that the heat loss from the absorber to the surroundings is decreased drastically compared to that of the collector without cover. Two covers further decrease the heat loss. If the double walled cover is ribbed, the strength of the cover is increased.

Figure 2.2 shows an example of the efficiency of an air base solar collector with transparent cover.

Comparing figure 2.1 and 2.2 it is seen that the solar collector with a transparent cover has a higher performance than a collector with no cover in front of the absorber.

2.3 Flow in the MF-panel

When the MF-panel is used as a heat exchanger between fresh air to the house and exhaust air from the house, the fresh air is supplied to one of the ducts while the exhaust air is supplied to the other. But which of the air flows should be outermost and which should be innermost?

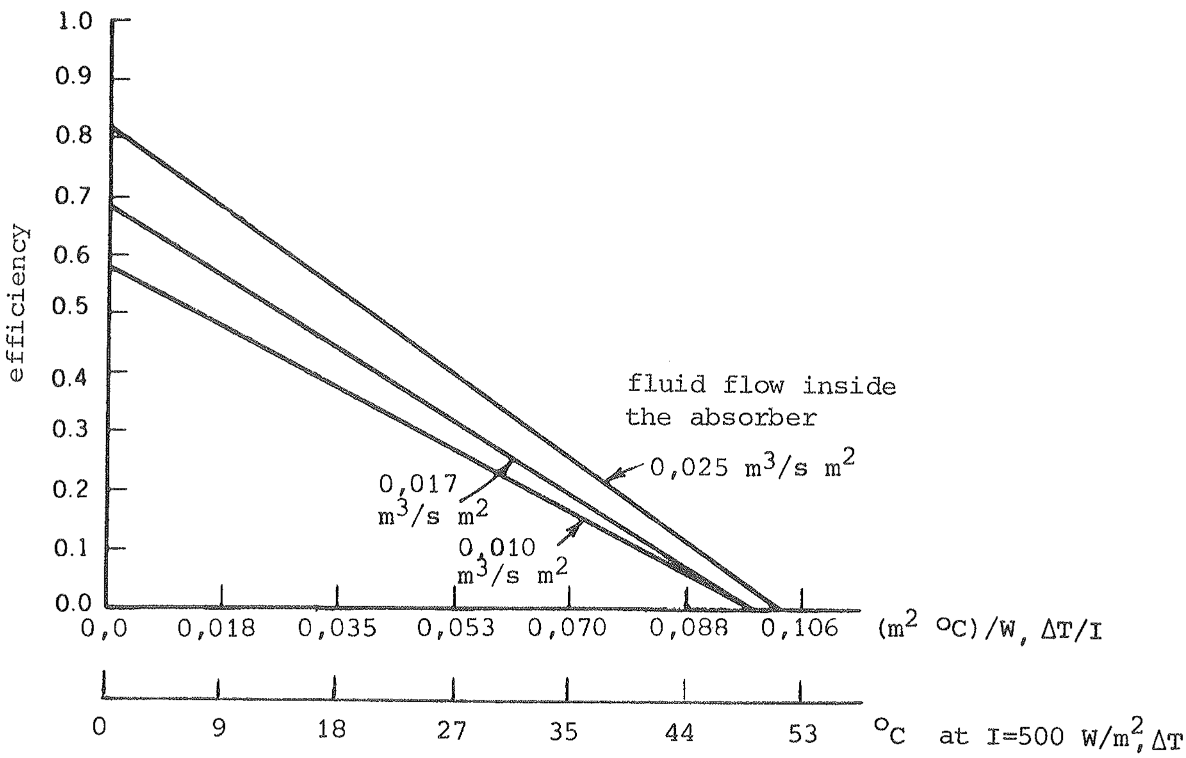

Figure 2.2 Efficiency curves for a typical air based solar collector. The efficiency is shown for three different flows through the absorber. The efficiency is here shown as a function of ΔT/I, where ΔT is the temperature difference between the absorber and the ambient air [°C], and I is the solar radiation [W/m^2]. ΔT is further shown for I=500 W/m^2 (Harris et al, 1985).

2.3.1 Metal sheet as outer cover

If the cover is a metal sheet, the air flow has to be as shown in figure 1.1 - the fresh air should be outermost. If the exhaust air was outermost, the absorbed solar radiation would be led directly to the outside air without heating the fresh air.

2.3.2 Transparent outer cover

The heat from the solar radiation is supplied at the wall between the two air flows, when the cover is transparent, it is therefore not that important for the utilization of the solar radiation which flow is the outermost, but a slightly higher performance can be obtained if the fresh air flows are outermost, as the solar energy will otherwise have to be conducted through the trapezium corrugated metal sheet before reaching the fresh air. If, however, the collector is only working as a solar collector (no exhaust air from the house), a higher performance can be obtained if the flow of fresh air to the house flows behind the trapezium corrugated metal sheet (the absorber), as the 'stagnant' air between the cover and the absorber will reduce the heat loss from the absorber.

If we investigate the heat loss from the panel, the lowest heat loss will occur if the air flows are as shown in figure 1.1. The fresh air is normally coldest, the loss through the cover is, therefore, minimized. When the warm exhaust air is led down along the outside surface of the insulated wall the heat loss through this wall will be reduced. The heat loss through the wall will be higher if the fresh air flows here, but the heat loss will be transported back to the house by the fresh air.

It is, as seen, not obvious how the air should flow in a MF-panel with a transparent cover. However, it is believed that the best performance per investment is obtained for the configuration shown in figure 1.1. By choosing this configuration it is furthermore possible to compare the performance of the two designs of the MF-element directly.

3 Structure of the Multi-Function Solar Energy Panel

The present chapter describes the two prototypes of the MF-panels developed within the project. The prototypes have been developed in cooperation with the Thermal Insulation Laboratory, the Architects Arne Meldgaard Aps and Techline International Energy Systems.

3.1 Selection of the trapezium corrugated metal sheet

Already from the beginning of the project it was decided that the trapezium shaped metal sheet in the MF-panel should be a Robertson BR profile, as this type of metal plate is commonly used as outer cover of the walls of industrial buildings. The building industry has therefore gained quite a lot of experience of mounting plates of this type, which may be of importantance in order to make the MF-panel known and popular. The plates are made of steel and have from the manufacturer a surface protection and they are available in several colours.

The Robertson BR profile is offered in several designs, three of these are shown in figure 3.1.

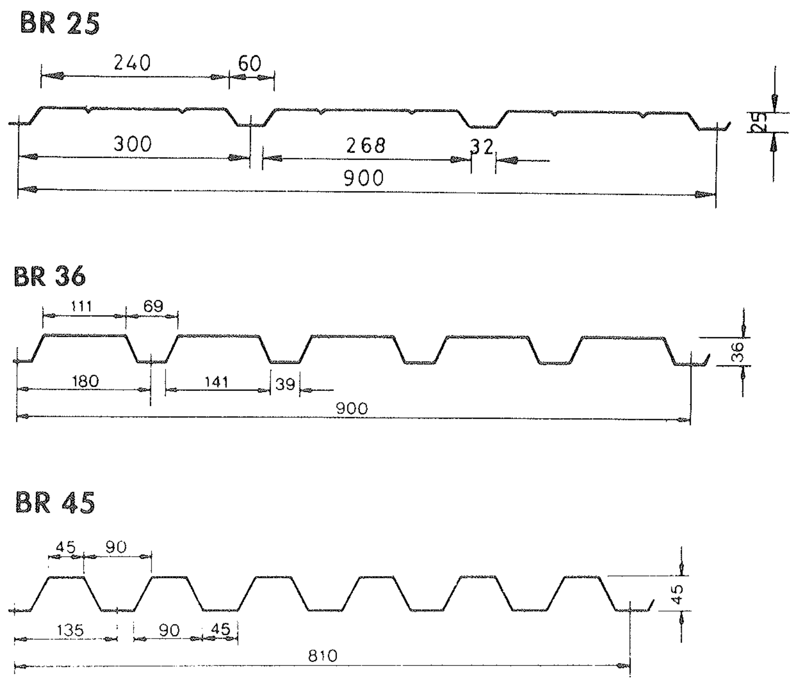

Figure 3.1 Three different designs of the Robertson BR profile.

Which of these profiles are best suited for a MF-panel? When designing heat exchangers and solar collectors it is very important to ensure that the heat exchange between the two fluids in the heat exchanger is as large as possible, and for the solar collector, that the heat transfer between the absorber and the fluid is considerable.

This means, on one hand, that the heat transferring area between the two fluids should be as large as possible, on the other, that the flow over the heat transferring area should be uniform across the width of this area. A uniform flow can be obtained by having a large pressure drop across the MF-panel.

As seen from figure 3.1 the profiles with the smallest height will have the smallest duct cross section area and thereby the largest pressure drop. But the highest profile has the largest heat transferring area. Calculations of the pressure drop across a MF-panels with different profiles were performed. For the calculation of the pressure drop a flow of 65 m^3/m^2h was chosen. 65 m^3/m^2h was chosen because it is the mean flow rate of the flow rates normally used in air based solar collectors (see figure 2.2, 65 m^3/m^2h = 0.018 m^3/m^2s). The calculations proved that the pressure drop across a MF-panel with the dimension 1.4x2.4 m^2 (see later) was too small to ensure a uniform flow no matter which profile was chosen. In order to have a uniform flow through the MF-panel, a large pressure drop at the inlet and/or the outlet of the panel is necessary. It was estimated that a pressure drop across the MF-panel of about 10 Pa at a flow of 65 m^3/m^2h would be sufficient to ensure a uniform flow rate over the cross section of the MF-panel.

As the pressure drop across the trapezium corrugated metal sheet was of no importance, the highest profile BR45 was chosen as this profile would give the largest heat transferring area. It was further decided that the profile should not touch the cover or the surface of the insulated wall behind the profile. If the profile had been in contact with the cover and the wall behind, the direct heat transferring area would have been reduced to 53%. The top and bottom of the profile touching the cover and wall will act as a fin, but as the material of the profile is steel with a low conductivity only a minor amount of heat will be transferred that way. The gap between the profile and the cover and the profile and the wall behind has been chosen to be 5 mm. The overall duct area for the cross section of the two duct systems is in the prototype 0.0375 m^2.

In a MF-panel with a metal sheet as outer cover the colour of the trapezium shaped profiles is not important - it should, however, not have a bright surface as this will reflect the radiation from the heated cover and thereby reduce the heat gain from the sun. In a MF-panel with a transparent cover the surface of the profile should preferably be mat black or at least a mat dark colour. The MF-panel will have to serve as outer surface of a building, so architects are of course interested in the possibility of changing the colour of the profile. The colour of the profile of the prototype has therefore not been chosen to be black but brown - it could have been dark blue, dark green etc.

3.2 Design of the prototypes

The prototypes of the MF-panels are developed according to the principle shown in figure 1.1. The MF-panels are primarily the heat exchangers between the fresh air to the house and the exhaust air from the house, but they will benefit from the solar radiance.

Figure 3.2-3.3 show the MF-panel developed within the project. The panel is constructed in such a way that it is possible to replace the outer cover. In this way it is possible to test both designs of the MF-panel: The outer cover is a metal sheet and the outer cover is transparent. For the two prototypes the following covers have been chosen:

1) a 1 mm steel plate painted mat black, and
2) a 10 mm double walled, ribbed polycarbonate plate - the walls are 0.5 mm thick.

The covers consist of two plates supported at the sides, the top and down the middle of the panel. When having a transparent cover the transparent area of the MF-panel (used for the characterization as solar collector) is 3.05 m^2. This area is, in the following, used to characterize the panel.

The insulated wall of the MF-panel consists of 100 mm mineral wool enclosed in 12 mm plywood, supported by laths. The panel is sealed so the two air flows cannot be mixed and no air can escape through the cover or through the insulated wall.

In order to secure a uniform flow across the panel the cross section of the outlet of exhaust air from the manifold was reduced to half the area of the cross section between the profile and the insulated wall - see figure 3.4. The same procedure was followed at the inlet of fresh air to the manifold - see figure 3.5. As shown later (chapter 5.3) this gave a pressure drop > 10 Pa across the panel for the fresh air at an air flow of 65 m^3/m^2h, but for the exhaust air the pressure drop was too low, so the cross section of the outlet was also reduced to half the area of the cross section between the profile and the insulated wall. Measurement of the air speed at the inlet of fresh air to the panel at an air flow rate of 65 m^3/m^2h showed an almost uniform air flow over the cross section. It is therefore to be believed that the flow through the panel is uniform, at least for flows greater than 65 m^3/m^2h.

Figure 3.6 shows the panel before the mounting of the trapezium corrugated metal sheet, note the lath to support the profile down the middle of the panel. Figure 3.7 shows the panel after the profile is mounted, note also here the lath down the middle of the profile. This lath supports the cover.

Figure 3.8 and 3.9 show the MF-panel with the cover of metal sheet and the transparent cover; the MF-panel is shown mounted at the test rig of the artificial sun at the Thermal Insulation Laboratory - see the next chapter.

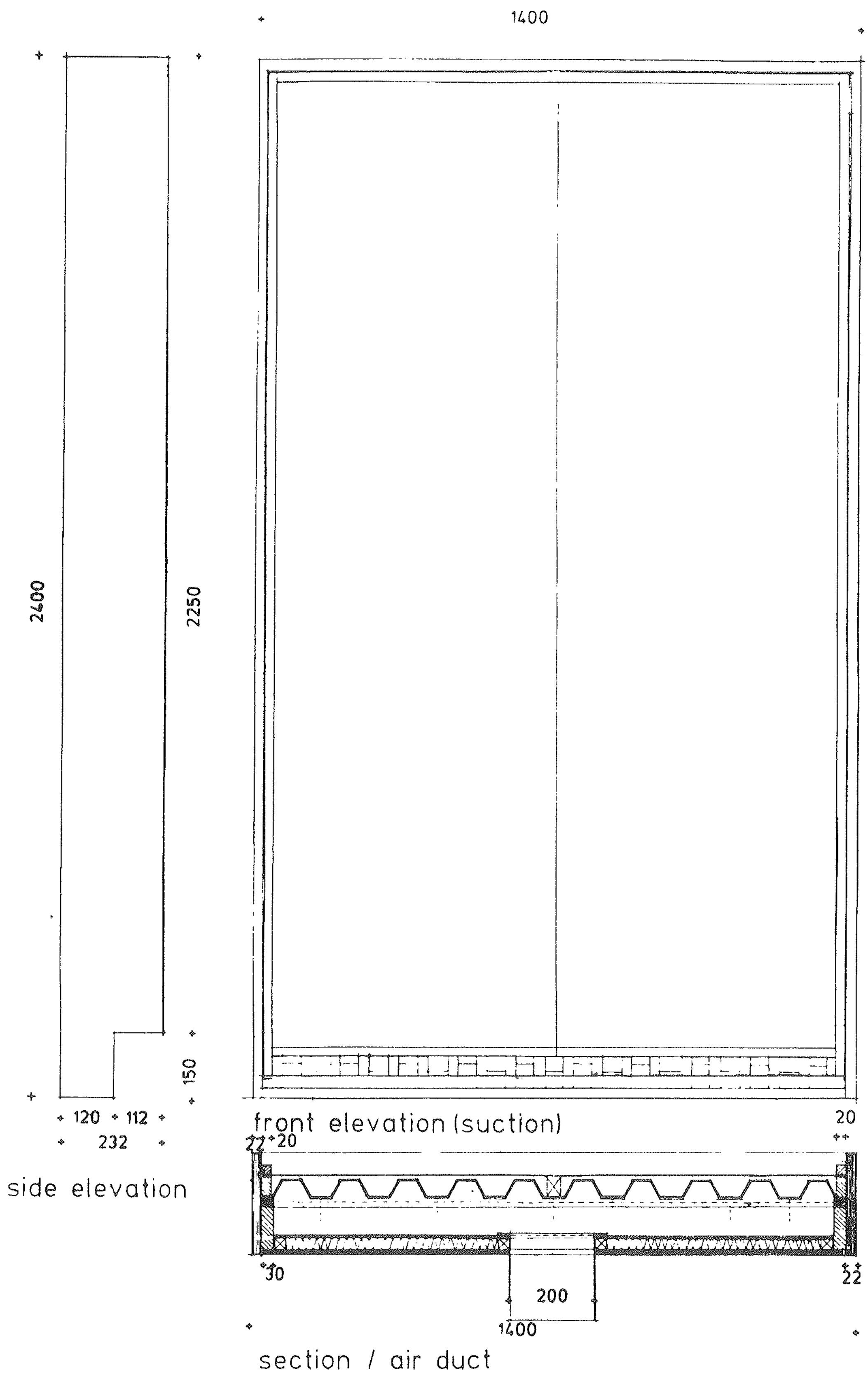

Figure 3.2 Drawings of the prototype of the MF-panel used for the project.

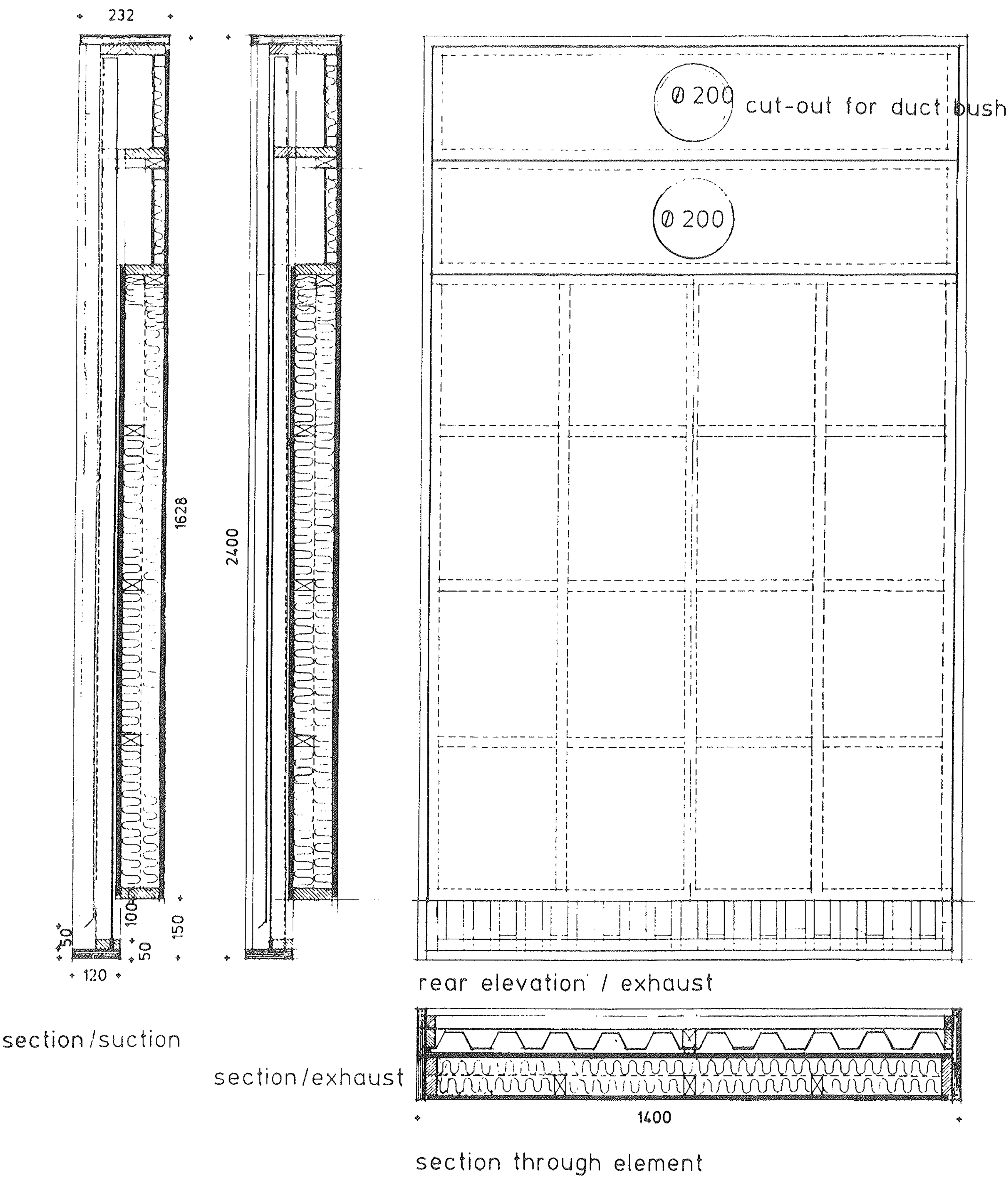

Figure 3.2 Drawings of the prototype of the MF-panel used for the project.

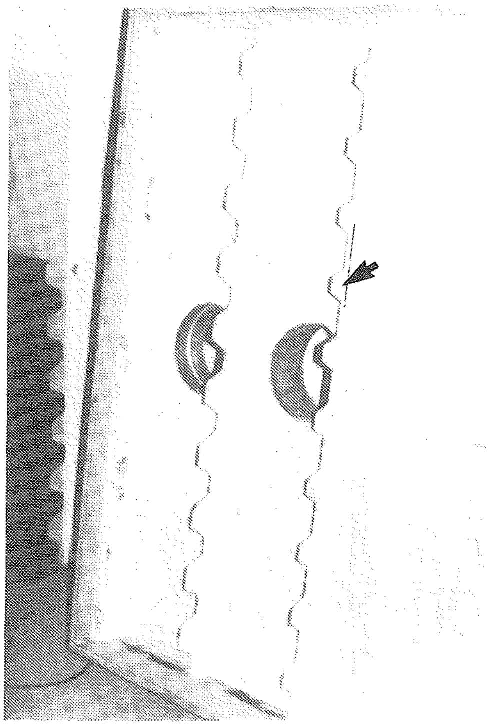

Figure 3.4 The reduction of the cross section at the outlet of exhaust air from the manifold.

Figure 3.5 The reduction of the cross section at the inlet of fresh air to the manifold.

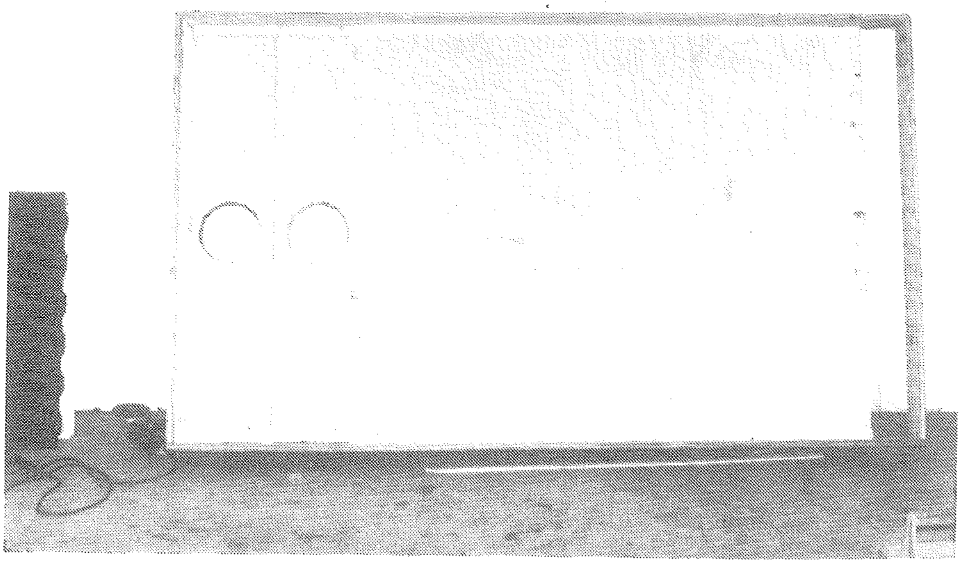

Figure 3.6 The MF-panel before mounting of the trapezium corrugated metal sheet.

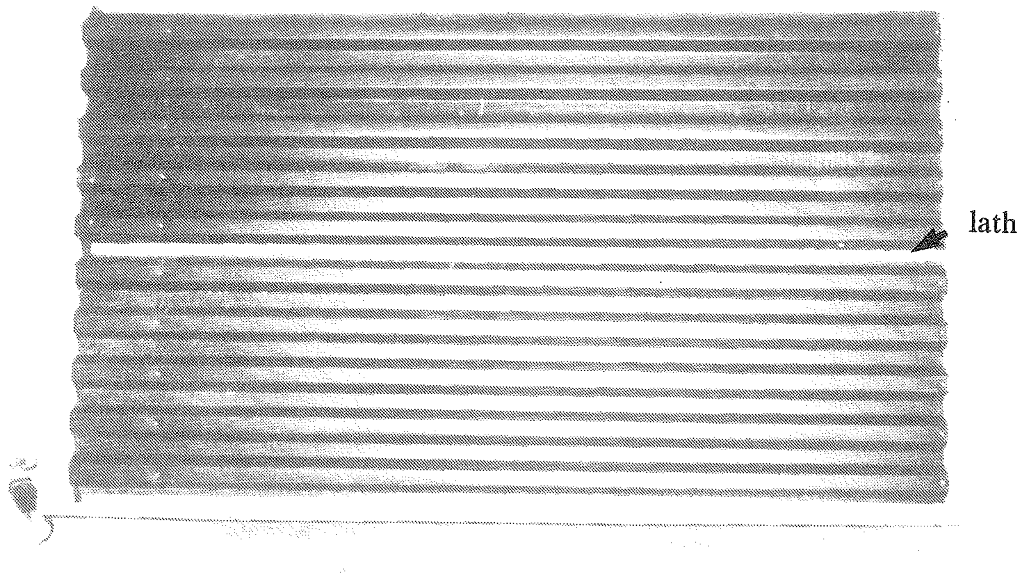

Figure 3.7 The MF-panel before mounting of the cover.

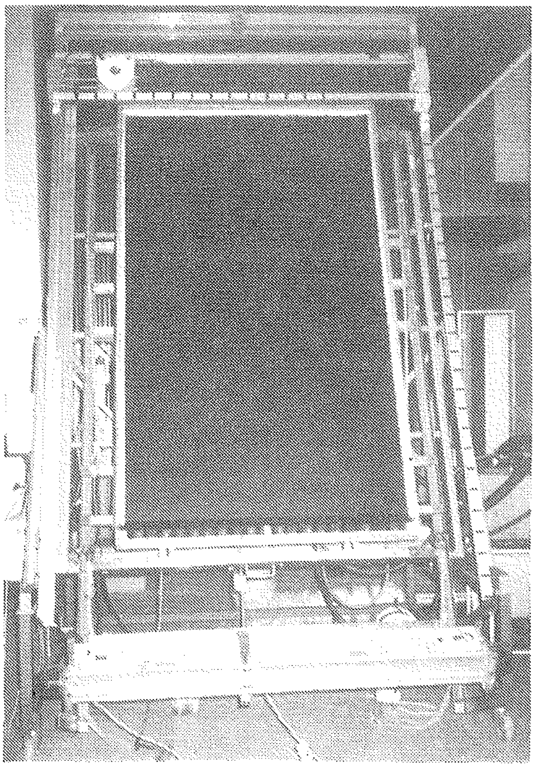

Figure 3.8 The MF-panel with a cover of metal sheet.

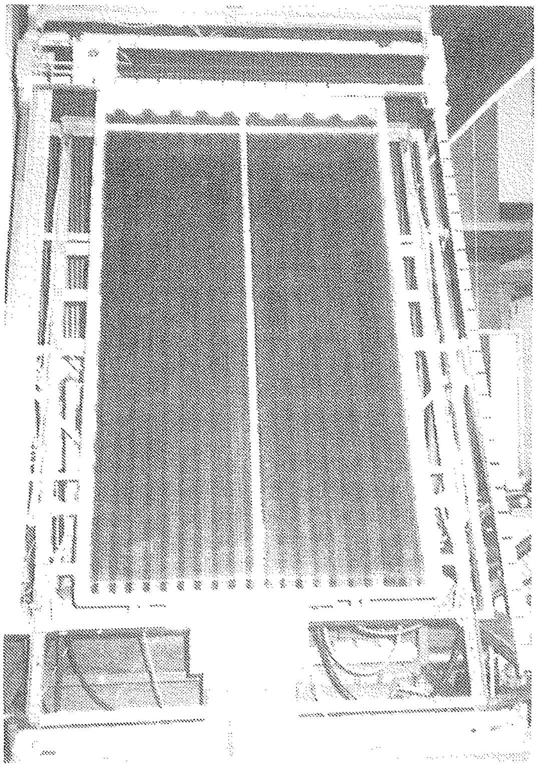

Figure 3.9 The MF-panel with a transparent cover.

4 Test of the MF-panel as solar collector

The aim of the present project has been to develop and test two prototypes of a MF-panel. In this chapter the results obtained from tests carried out on the two prototypes working only as solar collectors for preheating of fresh air are described.

4.1 Efficiency test

The efficiency of the MF-panel that only works as a solar collector for preheating of fresh air has been measured using the artificial sun at the Thermal Insulation Laboratory. The artificial sun consists of an array of 36 mercury halogen lamps (Thorn-CSI). The solar collector - placed in a test rig (figure 4.1) - is exposed to an irradiation of about 900 W/m^2. The test rig is tilted so the plane of the rig is parallel with the artificial sun.

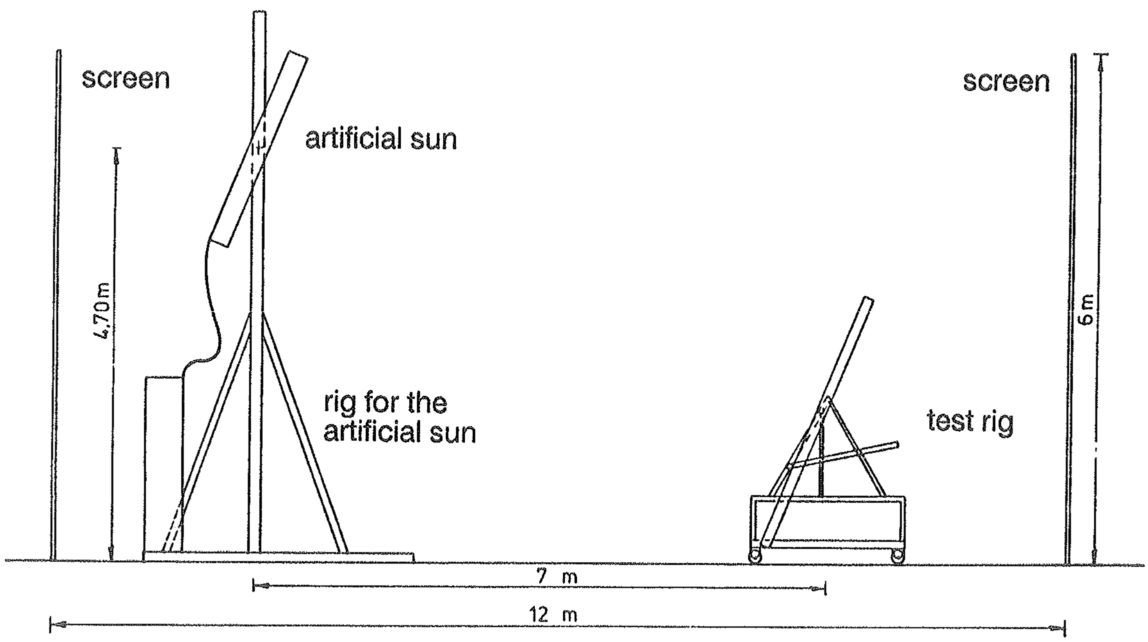

Figure 4.1 The artificial sun and test rig at the Thermal Insulation Laboratory.

The size of the plane at the test rig is 1.5x2.5 m^2, so in order to have some free space for mounting the MF-panel, the panel was chosen to be 1.4x2.4 m^2.

4.1.1 The test arrangement

The test rig of the artificial sun is equipped with a liquid system for test of a water based solar collector. This system could of course not be used, nor could the data acquisition system be connected to the test rig.

Instead the MF-panel was connected to a ventilator via a flexible duct and an orifice. Figure 4.2 shows the flexible duct connected to the MF-panel. The inlet to the inner duct of the MF-panel was sealed by means of insulation and tape. This was done in order to prevent an air flow through this duct, resulting in a heat loss, which would decrease the efficiency of the MF-panel as solar collector.

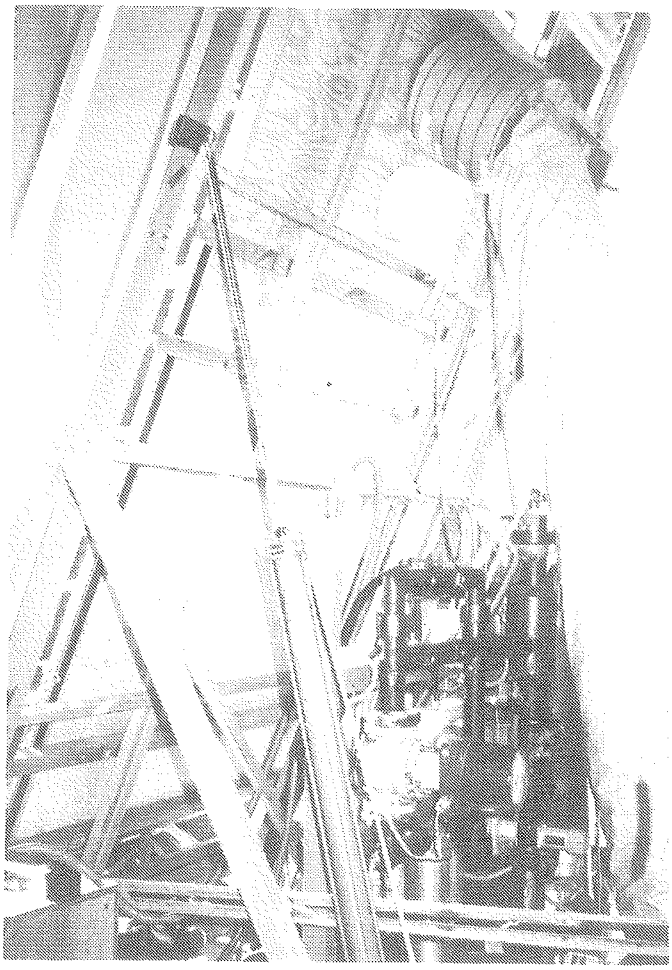

Figure 4.2 The flexible duct connected to the MF-panel.

Figure 4.3 shows the measuring equipment. The air flow was, as already mentioned, measured by means of an orifice. The flow is calculated from the measured pressure drop across an orifice. The temperatures at the inlet and outlet of the MF-panel were measured by means of thermocouples. The temperature difference across the panel was measured by means of a thermopile. The thermocouples and the thermopile were mounted in two ducts with three perforated plates placed with holes out of alinement (figure 4.4). This was done in order to make the flow very turbulent and thereby get the air well mixed before the temperatures and the temperature difference were measured.

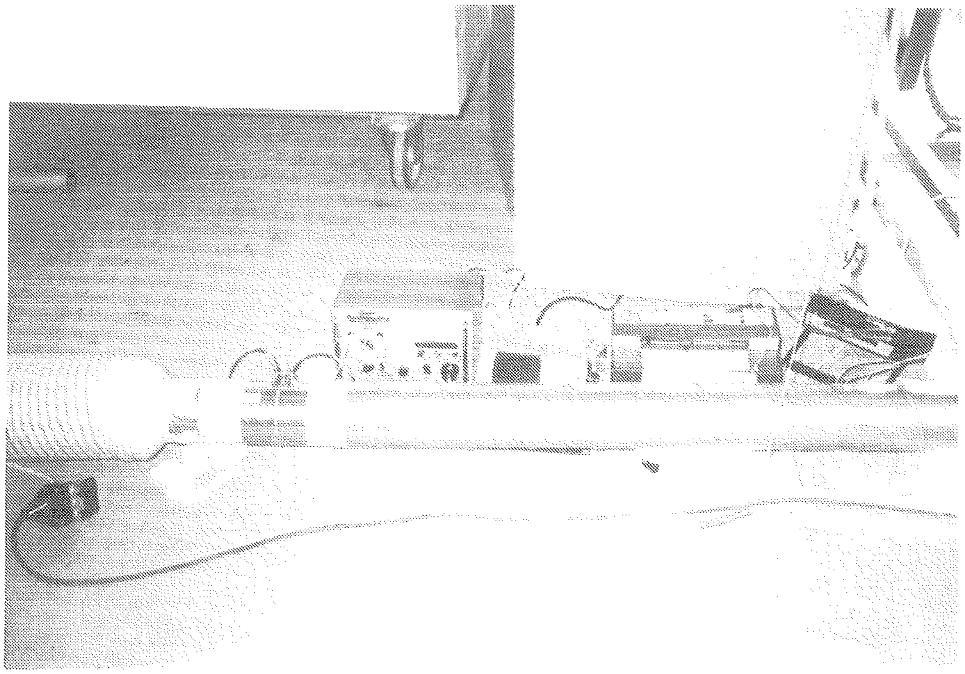

Figure 4.3 The measuring equipment in the test arrangement for measurement of the efficiency of the MF-panel as solar collector.

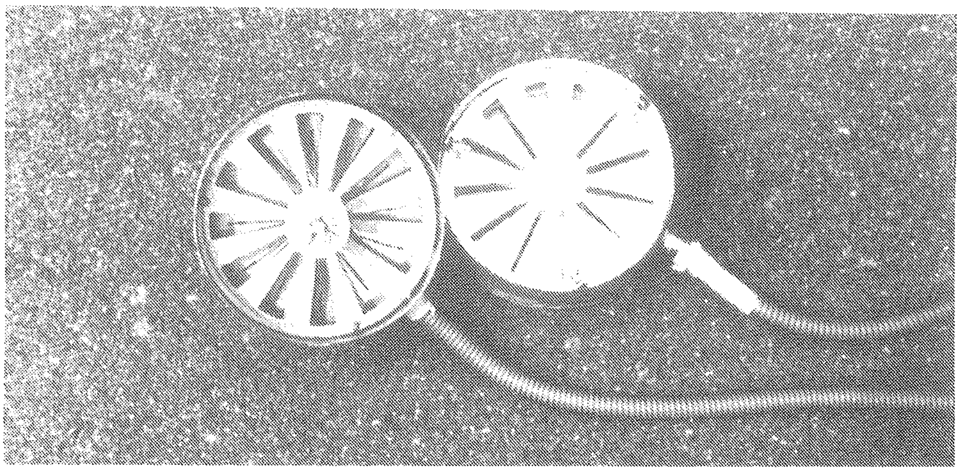

Figure 4.4 The measuring ducts with the thermocouples and the thermo pile.

Comparing figure 3.8 and 3.9 with figure 4.4 it is seen that it is impossible to connect the measuring duct to the inlet to the MF-panel. Instead the measuring duct was placed just below the panel and shielded from the radiation (from the artificial sun) by means of a reflecting metal sheet (figure 4.5). In order to measure the real inlet temperature to the panel, a small ventilator blew air at the measuring duct.

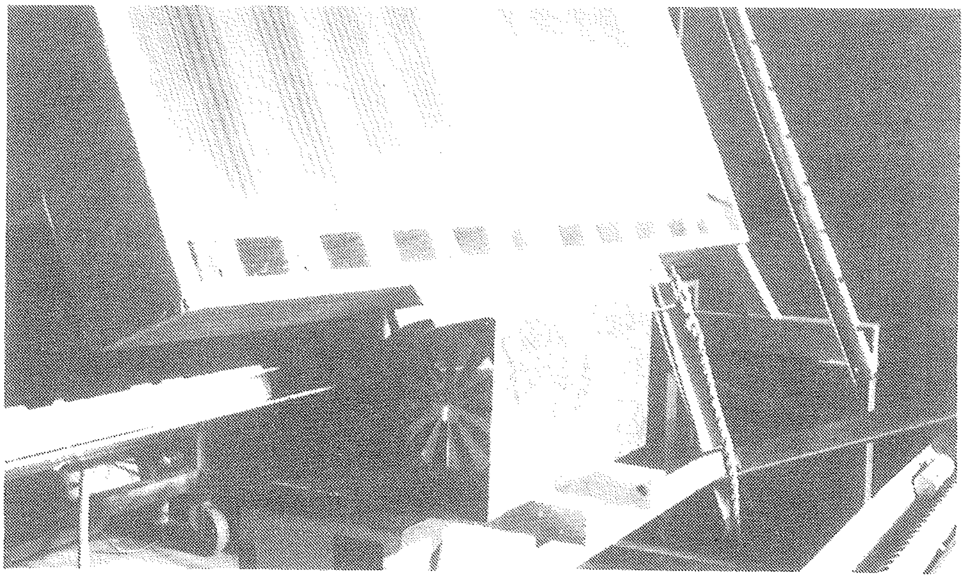

Figure 4.5 The measuring duct containing a thermo couple and one part of a thermopile shielded from the artificial sun by a reflecting metal sheet.

4.1.2 Results from the efficiency test

The efficiency of the MF-panel, that works only as a solar collector, is found using the following equation:

$$\eta = \frac{v \rho c_p \Delta T}{A I} \qquad (4.1)$$

where: v is the flow rate through the MF-panel [m³/h],
ρ is the density [kg/m³],
c_p is the heat capacity [J/kgK],
ΔT is the temperature difference across the MF-panel [K],
A is the characteristic area of the MF-panel [m²],
I is the radiation from the artificial sun [W/m²].

At the test rig there is a facility to blow air up along the cover of the solar collector. The two prototypes have, therefore, been tested both with and without the influence of 'wind'. When wind was simulated, the air stream was about 2 m/s. When no wind was simulated there was of course a small air flow due to heating of the air above the cover of the panel. The mean air flow for the panel with a metal sheet as cover was about 0.4 m/s, while, for the panel with the transparent, double walled, ribbed cover, it was about 0.2 m/s.

During the test procedure of water based solar collectors at the Thermal Insulation Laboratory, the wind speed along the covers of the collectors is 5-6 m/s. In this project a wind speed of 2 m/s was chosen because several years of measurements (Østergaard Jensen, 1986b and 1987) have proved that the wind speed along a tilted, south orientated plane very seldom exceeds 2 m/s and normally stays below 1 m/s.

In figure 4.6 the results from the test of the MF-panel acting purely as a solar collector for preheating of fresh air are shown. The efficiency of the MF-panel with transparent cover is as expected higher than the efficiency of the MF-panel with a metal sheet as cover. The figure also shows that the MF-panel with a metal sheet as cover is much influenced by wind along the cover, while the influence of wind on the MF-panel with transparent cover is negligible.

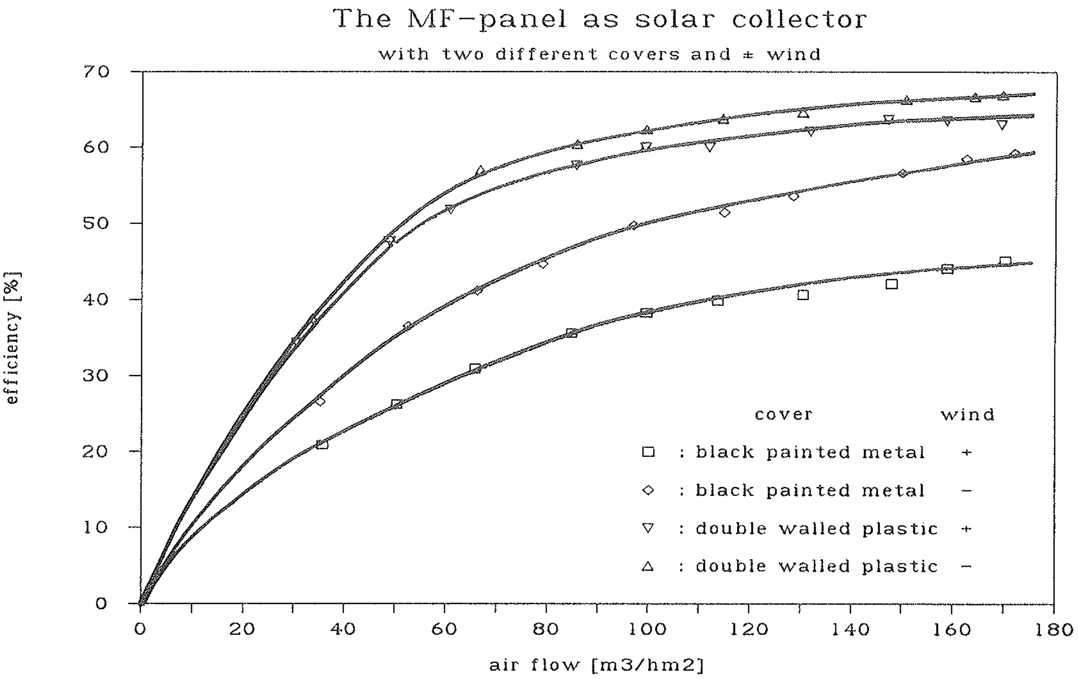

Figure 4.6 The results from tests made on the MF-panel that works only as solar collector for preheating of fresh air. The efficiency has been measured with and without a simulated influence of wind of 2 m/s.

When comparing figure 2.2 with figure 4.6 it seems that the MF-panel is more efficient than a normal air based solar collector. This is, however, not true. The MF-panel is operating with an inlet temperature equal to the ambient temperature, it will, therefore, be necessary to compare the values given in figure 4.6 with the values given where the curves are crossing the x-axis ($\Delta T/I=0$) in figure 2.2. Then it is seen, that the MF-panel is not working quite as well as a normal well designed air based collector - at 90 $m^3/m^2h = 0.025$ m^3/m^2s - the normal air based collector will have an efficiency of more than 80% while the MF-panel with a transparent cover and no wind along the cover will have an efficiency of about 60%. This could have been predicted because a collector with the fluid in front of the absorber is a type of collectors that is not working as well as collectors with transparent covers. The reduced efficiency is, however, as seen later, more than compensated due to the contribution from the MF-panel working as heat exchanger.

The results shown in figure 4.6 are obtained for the prototypes described in chapter 3. The question is now, will the efficiency change if the dimensions of the panel are changed, if eg the panel is made longer? This will be discussed in section 4.3.

The first test carried out on the MF-panel showed some strange results - they are shown in figure 4.7. It seems that when the flow rate through the collector is increased the efficiency sometimes drops.

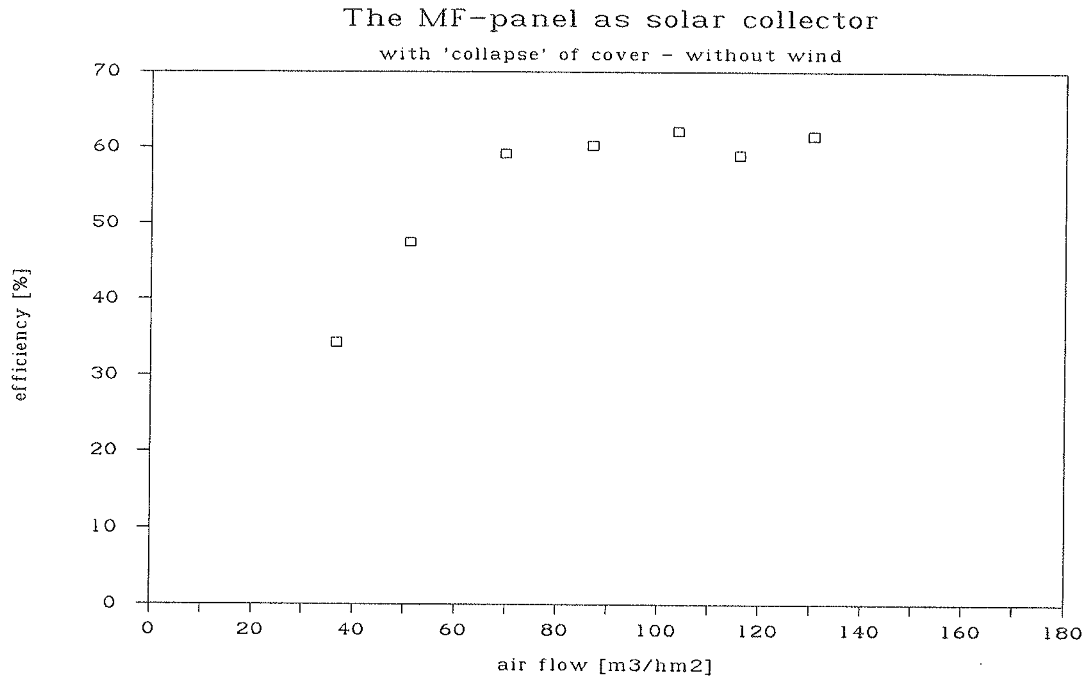

Figure 4.7 Results from the first test on the MF-panel with transparent cover.

What happened was, that due to the heat, the cover became a little plastic. When the flow rate through the panel was increased, the cover was sucked in against the trapezium shaped sheet and thereby reduced the area of the absorber which was in contact with the air stream. This illustrates the remarks made in paragraph 3.1, that if there is no gap between the cover and the trapezium corrugated metal sheet and between the profile and the wall behind, the performance will be decreased. Figure 4.7 actually shows the performance of several different collectors, this is shown more clearly in figure 4.8.

To overcome this problem small rings of transparent acrylic, each 5 mm high, were placed between the cover and the profile, as seen in figure 4.9.

4.1.3 Uncertainties

Figure 4.6 shows the measured efficiencies of the MF-panel working as a solar collector. The question is, however, how well the efficiencies are determined. To answer this question the uncertainties of the measured efficiencies have been calculated.

The uncertainties were found from the uncertainties on the measuring equipment. Only the three main uncertainties have been taken into consideration. These uncertainties are:

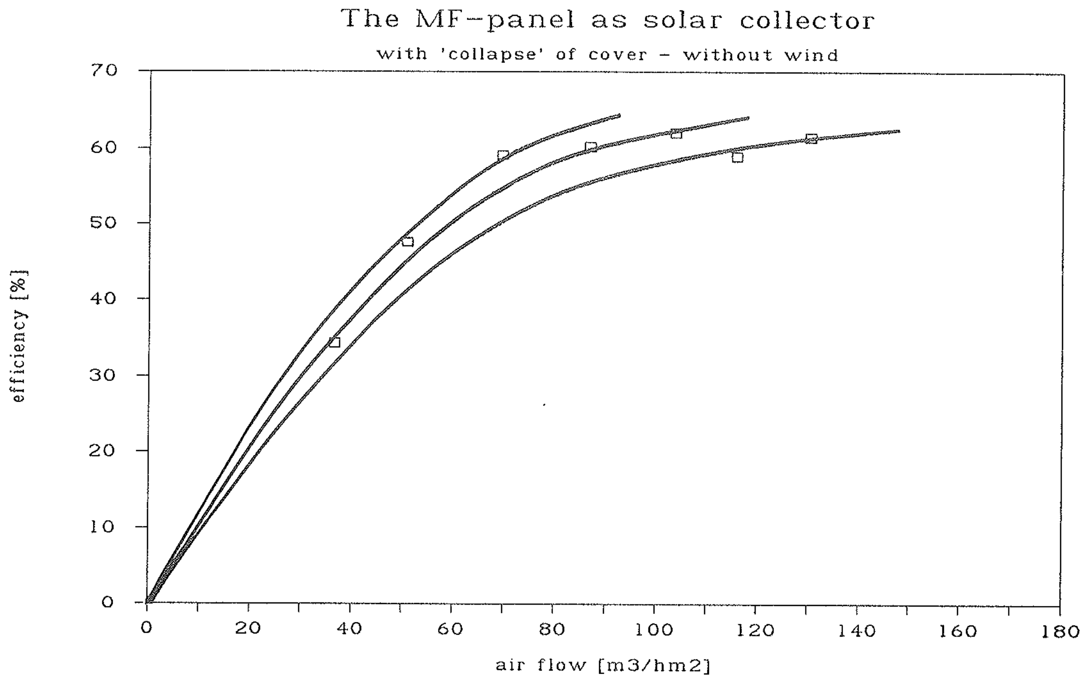

Figure 4.8 Figure 4.7 with curves for several different solar collectors.

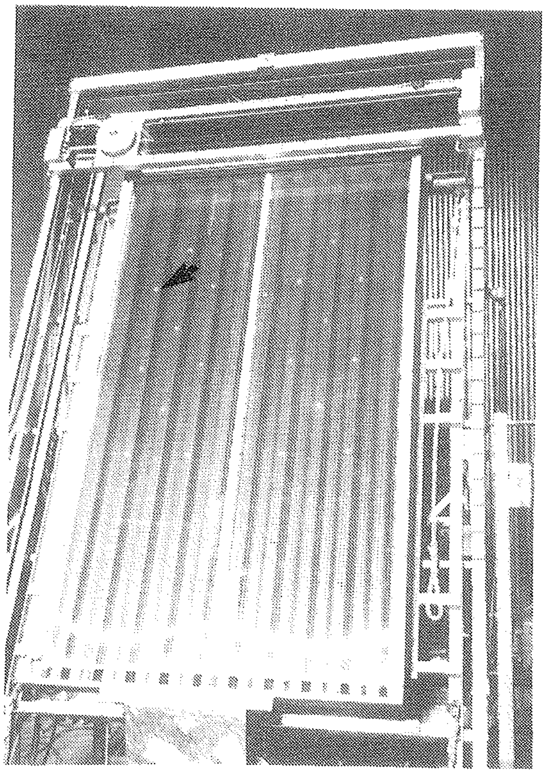

Figure 4.9 The MF-panel after the small rings of transparent acrylic were placed between the cover and the trapezium corrugated metal sheet.

Fläkt flow measuring device: 5%
Micro manometer: 0-12.5 mmhg (0-400 m^3/h) : 0.125 mmhg
12.5-25 mmhg (400-564 m^3/h) : 0.25 mmhg
Temperature difference: 0.3 °C.

It is assumed that the three uncertainties are independent. The law of accumulation can, therefore, be used. The uncertainty of the measurements is therefore - knowing that to find the flow rate it is necessary to extract the square root of the pressure drop (Δp) across the flow measuring device - :

$$\frac{s(\eta)}{\eta} = \sqrt{\left(\frac{1}{2}0.05\right)^2 + \left(\frac{1}{2}\frac{s(\Delta p)}{\Delta p}\right)^2 + \left(\frac{s(\Delta T)}{\Delta T}\right)^2} \tag{4.2}$$

where: Δp is the pressure drop across the flow measuring device [Pa],
ΔT is the temperature difference across the MF-panel [K].

In figure 4.10 the calculated uncertainties of the measured efficiencies of the MF-panel with transparent cover and no wind are shown. The uncertainties are shown as full lines in order to make the figure more clear. The uncertainties of the other configurations of the MF-panel show a similar picture.

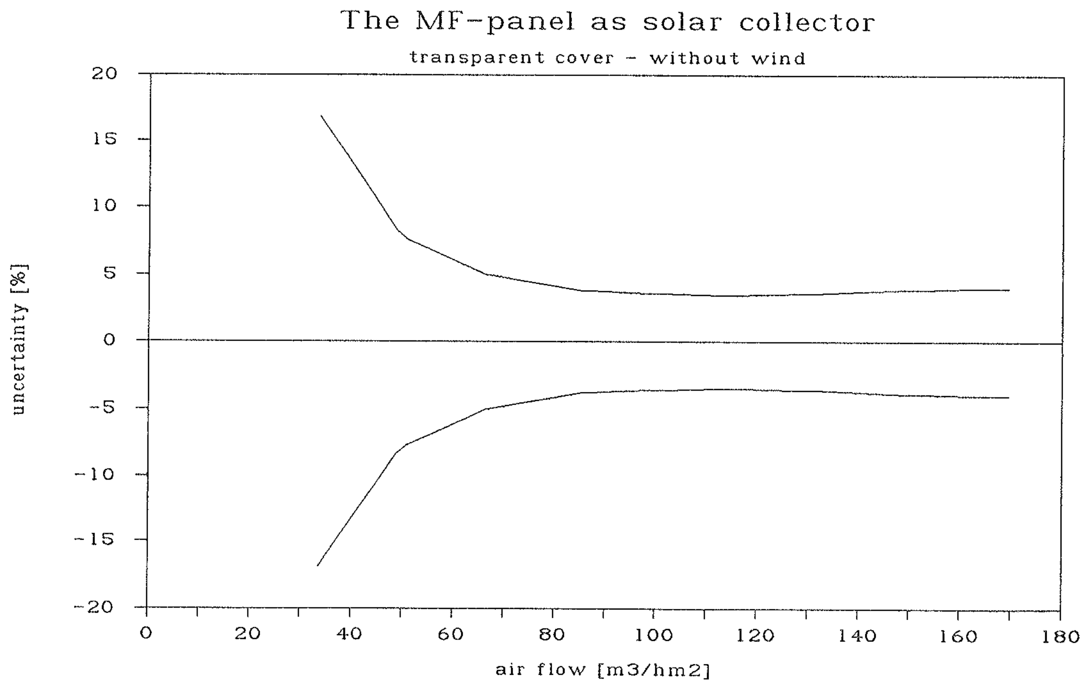

Figure 4.10 The uncertainties of the measured efficiencies of the MF-panel with transparent cover and no wind.

For flow rates higher than 50 m^3/m^2h the efficiencies are very well determined. The uncertainties are here between ±3 and ±5%. The uncertainty on the temperature difference can seem rather high, but in fact it is hardly noticed in the overall uncertainty. Only at very high flow rates (higher than shown here) the temperature difference across the collector will fall so much, that the uncertainty on the temperature difference will become dominant.

4.2 Stagnation temperatures

After the efficiency of the MF-panel had been measured, the MF-panel was exposed to a stagnation test. During a stagnation test the solar collector is exposed to maximum irradiation (here 900 W/m^2) without any flow through the collector. This is done to see how the collector will react when it is exposed to the worst possible conditions. The temperature of the collector is measured. The maximum temperature in the collector (the temperature of the absorber) and a visual inspection of the collector after the stagnation test will give a hint about the reliability of the collector.

The ducts from the manifolds of the MF-panel was sealed in order to prevent any ventilation of the panel. Figure 4.11 shows the results of the stagnation test of the MF-panel with the two different covers. The stagnation temperature is measured at the absorber - at the cover for the panel with the metal sheet, and at the trapezium corrugated metal sheet for the panel with transparent cover.

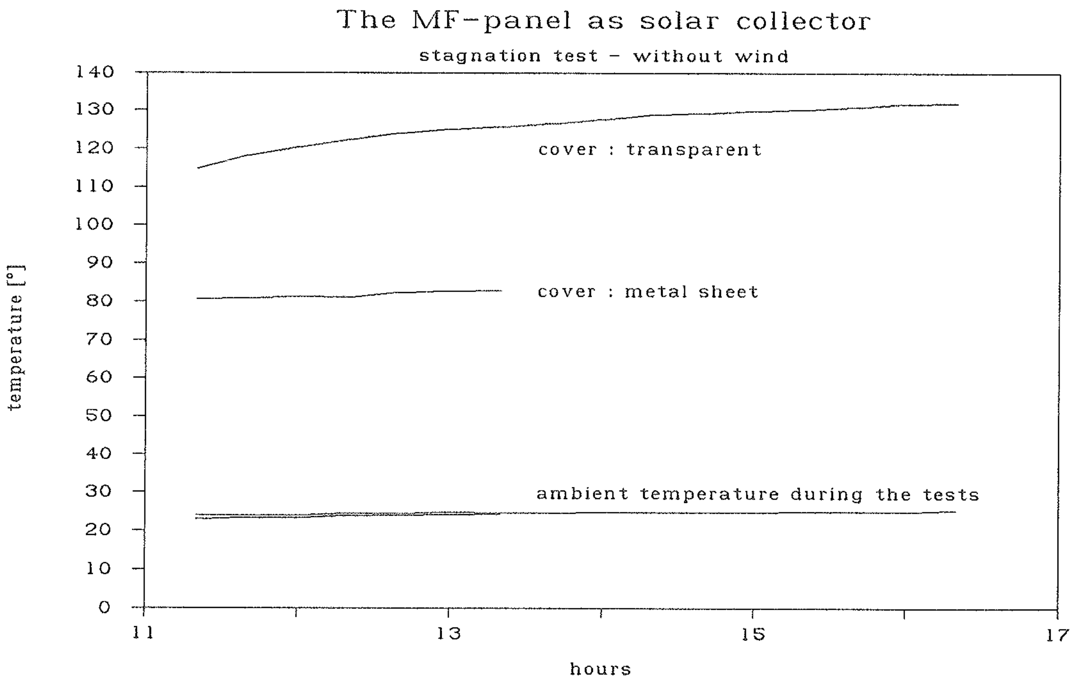

Figure 4.11 The results of the stagnation tests.

Even if the MF-panel was in stagnation for more than five hours the temperature of the absorber was still increasing slowly. The reason is that the MF-panel is a rather heavy construction with a large heat capacity. In reality the panel will not be exposed to these extreme conditions for very long.

Examining figure 4.11 it can, therefore, be said that the stagnation temperature of the MF-panel will not exceed 135 °C if the cover is transparent and not exceed 85 °C if the cover is a black painted metal sheet. These stagnation temperatures correspond very well to the stagnation temperatures found for water based solar collectors with and without a transparent cover in front of the absorber.

When the MF-panel was in stagnation there was a heavy smell of exhaust products from plywood in the hall. It is, therefore, not advisable to use plywood or any other material which will degas. If such material is used it should be kept at a low temperature, eg by encapsulating the material in the insulation.

4.3 Theory

In this project, it has not been possible neither been the aim to develop a theory for prediction of the thermal processes occurring in a MF-panel. A first attempt has, however, been made in order to see if it was possible to give an estimate of the performance of the MF-panel working as a solar collector.

It is somewhat complicated to create the theory for a solar collector. It was therefore decided to use an already developed theory for a solar collector very much like the present (Duffie et al, 1974). The applied theory is for a collector as outlined in figure 4.12. As seen the main difference between the collector in figure 4.12 and the present is that the absorber in the figure is a flat plate.

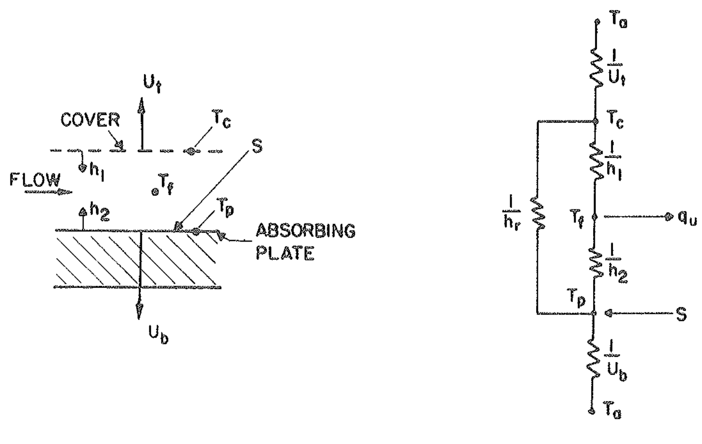

Figure 4.12 Outline of the solar collector for which the theory is developed.

In traditional terms the performance of a solar collector can be written:

$$q_u = F'F''(I(\tau\alpha)_e - U_L(T_i - T_a)) \tag{4.3}$$

where: I is the solar irradiation hitting the panel [W/m2],
T_i is the inlet temperature to the panel [°C] and
T_a is the ambient temperature [°C].

As the inlet temperature is equal to the ambient temperature the efficiency of the MF-panels working as solar collectors can be found from:

$$\eta = F'F''(\tau\alpha)_e \tag{4.4}$$

where:

$$F' = \left(1 + \frac{h_r U_t}{h_r h_1 + h_2 U_t + h_2 h_r + h_1 h_2}\right)^{-1} \tag{4.5}$$

$$h_r = \frac{\sigma(T_1^2 + T_2^2)(T_1 + T_2)}{\epsilon_1^{-1} + \epsilon_2^{-1} - 1} \tag{4.6}$$

where: σ is Stefan-Boltzmann's constant = 5.6697 10^{-8} W/m2K4.
ϵ_1 and ϵ_2 are the emissivities of the cover and absorber.

Only small errors will occur if, instead of T_1 and T_2, only one temperature is used - the mean temperature T_m, as stated in the following equation:

$$h_r = \frac{4\sigma T_m^3}{\epsilon_1^{-1} + \epsilon_2^{-1} - 1} \tag{4.7}$$

U_t can eg be found from figure 4.13. The top heat loss in figure 4.13 is shown for a 45° tilt of the collector. The MF-panel was tested at a tilt of 67.5°. According to Duffie et al (1974) the change of tilt can be accounted for by multiplying by a correction factor - in this case 0.973.

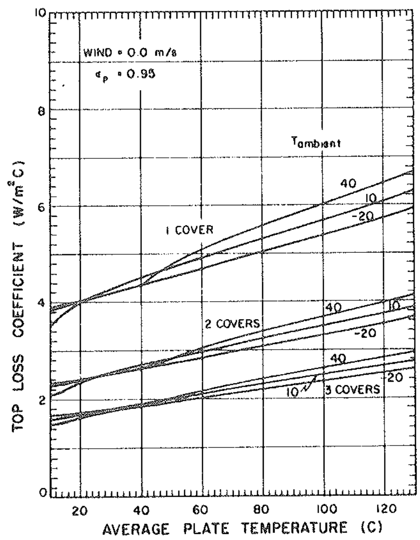

Figure 4.13 The top heat loss for different cover systems (1, 2 and 3 covers), at different collector temperatures and ambient temperatures and with no wind speed along the surface of the cover (Duffie et al, 1974).

h_1 and h_2 are assumed to be equal and found from:

$$h = \frac{Nu\,\lambda}{D_h} \tag{4.8}$$

$$Nu = 0.0158(Re_{D_h})^{0.8} \tag{4.9}$$

$$D_h = \frac{4A}{P} \tag{4.10}$$

where: Nu is the Nusselt's number,
λ is the conductivity of the air [W/mK],
D_h is the hydraulic diameter [m],
Re_{Dh} is the Reynolds' number for the air,
A is the area of the cross section of the duct formed by the trapezium corrugated metal sheet and the cover [m],
P is the perimeter of the above mentioned duct [m].

$$F'' = \frac{GC_p}{F'U_L}\left(1 - e^{-[F'U_L/GC_p]}\right) \tag{4.11}$$

where: G is the mass flow rate per unit collector area [kg/m²s],
C_p is the heat capacity of the air [J/kgK].

$$U_L = \frac{U_t + U_b}{1 + \frac{(U_t + U_b)h_2}{h_1 h_2 + h_1 h_r + h_r h_2}} \tag{4.12}$$

Due to some reflection between the cover and the absorber the effective transmittance-absorptance product $(\tau\alpha)_e$ can be written (Svendsen, 1985):

$$(\tau\alpha)_e = 1.01\,\tau\alpha \tag{4.13}$$

τ is the transmittance of the cover and α is the absorptance of the absorber.

Using the above described formula a prediction of the efficiency of the MF-panel working as a solar collector has been given. The chosen cases are the measurements for the MF-panel with transparent cover and no wind along the surface of the cover.

It is assumed that there is no air movement along the surface of the cover so the top heat loss (U_t) from figure 4.13 can be used. The transmittance (τ) of the cover is assumed to be 0.84 and the absorptance of the absorber (α) is assumed to be 0.95. The emissivities of the cover and the absorber are also assumed to be 0.95. The flow rate and the mean temperature of the air stream from the measurements have been used for the calculations.

Figure 4.14 shows the comparison between the measured and predicted efficiencies of the MF-panel working as a solar collector. In the figure the uncertainties of the measurements are also shown. The uncertainties are shown as full lines just to make the figure more clear.

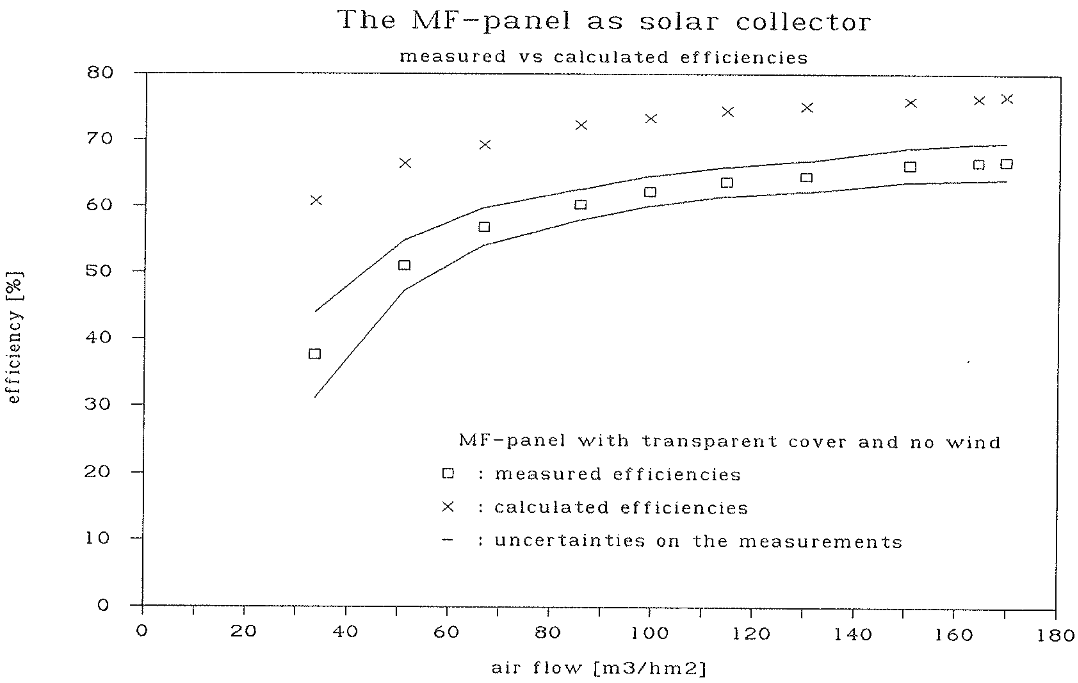

Figure 4.14 Measured and predicted efficiencies of the MF-panel acting as a solar collector.

The predicted efficiencies are, as shown, always much larger than the measured efficiencies - 15-60% larger, largest for small flow rates. The reason why there is such a bad agreement may be that the theory is developed for a flat plate absorber and not a corrugated one. The transmittance and emissivity of the cover and the absorptance and emissivity of the absorber have not been measured, if they differ from the assumed values it will of course influence the predictions. The difference can also be caused by a shortcut between the two air caps, so that colder air is sucked in from the air gap where the exhaust air normally flows.

Even if the described theory does not predict the same efficiency as the measurements, the theory will be used to investigate how a change of dimensions of the MF-panel will influence the efficiency. It is to be hoped that the theory will show the same trend as the measurements would have done.

Using the theory the efficiency of the situations shown in figure 4.14 has been calculated - the only change is that the panel is twice as long as the prototypes. The width, flow rate per m^2 and all other parameters are similar to those used for the test. The calculations show that the efficiency will be increased by 1.5-8% for the situations given in figure 4.14 - the increase will be highest for low flow rates. The increase of efficiency is caused by the fact that the total flow rate in the panel is twice as high while the cross section of the duct in the panel is the same. The air speed is therefore increased causing a higher heat transfer between the absorber and the air.

Even if we cannot say for certain that the trend of the model is the same as it would be in real life, we can conclude that the performance of the MF-panel is likely to be increased by making the panel longer. But when making the panel longer the pressure drop across the panel will also be increased and lead to increasing power demand of the ventilators. An optimization process is necessary in order to find the optimal length of a MF-panel and maybe reduce the pressure drop across the inlet and outlet.

The above described example shows that further work is necessary in order to establish a theory for prediction of the efficiency of the MF-panel acting as a solar collector. Such a theory is necessary if an optimized performance of the MF-panel is wanted.

5 Test of the MF-panel as heat exchanger

In this chapter the results from tests carried out on the two prototypes acting purely as heat exchanger between the fresh air to the house and the exhaust air from the house are described.

As the aim was to measure the efficiency of the MF-panel working only as a heat exchanger the measurements were performed late in the afternoon and mainly in the evening after sunset to avoid the influence of solar irradiation.

In a normal Danish ventilating system the flow rate of the exhaust air is about 10% higher than the flow rate of fresh air. This creates a small depressurization of the building and in that way it also prevents moisture from penetrating into the walls. If nothing is mentioned the tests are performed with a flow rate of the exhaust air 10% higher than the flow rate of the fresh air. The results will be characterized by the flow rate of the fresh air.

5.1 Efficiency test

The efficiency of the MF-panels acting purely as heat exchangers between fresh air and exhaust air has been measured in an experimental building (the SPTF - Solar Pilot Test Facility) at the Thermal Insulation Laboratory. The MF-panel was mounted in the gate of the experimental building in such a way that the panel became part of the wall. Figure 5.1 and 5.2 show the MF-panel with two different covers mounted in the gate of the experimental building.

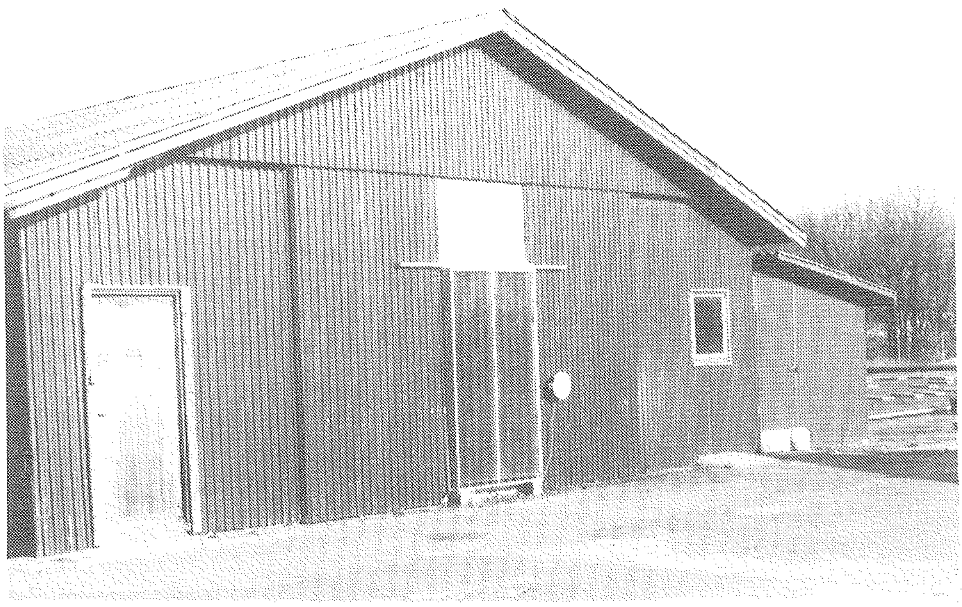

Figure 5.1 The MF-panel with transparent cover mounted on the experimental building.

The way the MF-panel was mounted in the experimental building caused the exhaust air to be sucked in very easily together with fresh air, specially if it was a little windy. Due to this it was difficult to obtain stable conditions - the measured values were fluctuating. The inlet of fresh air was therefore isolated from the exhaust air as shown in figure 5.3.

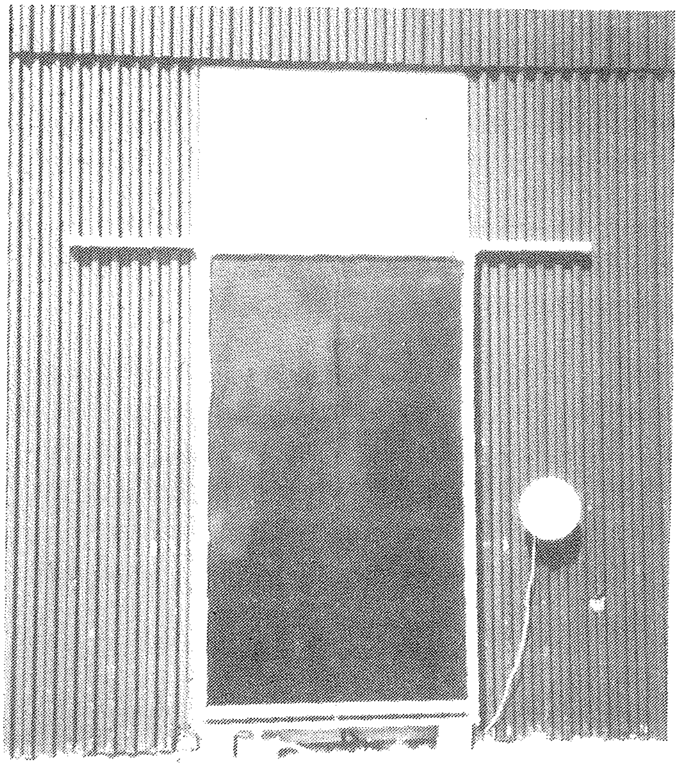

Figure 5.2 The MF-panel with a metal sheet as cover mounted on the experimental building.

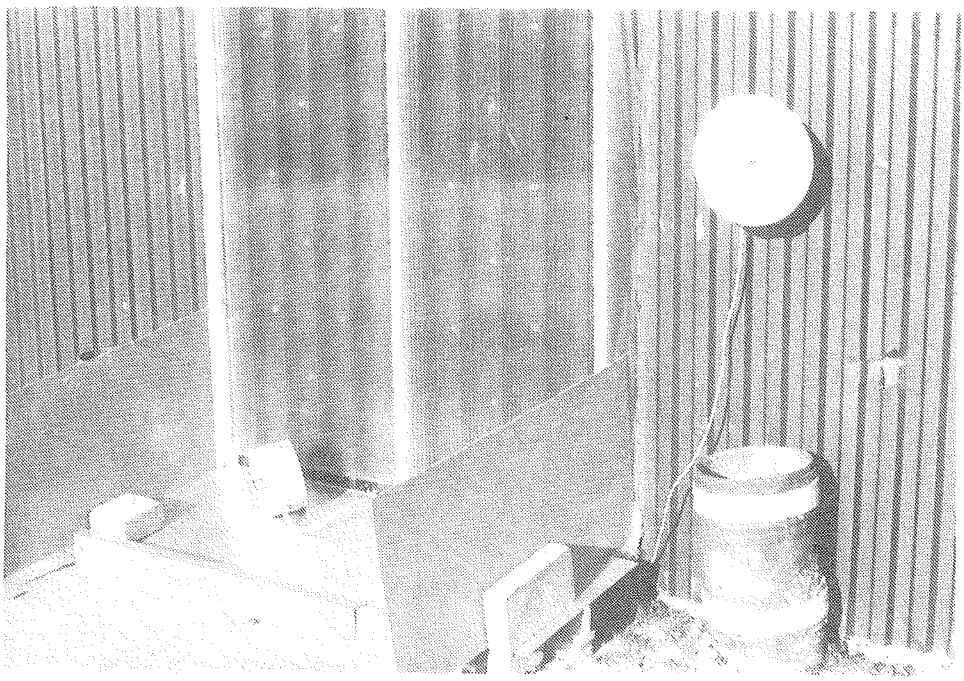

Figure 5.3 The picture shows how the suction air is isolated from the exhaust air. During measurements a small ventilator blew air at the 'measuring duct' to ensure that the measured temperature was identical to the temperature of the fresh air sucked into the MF-panel.

5.1.1 Test arrangement

Figure 5.4 shows the test arrangement for test of the MF-panel as a heat exchanger. Two flexible ducts were connected to the inlet and outlet of the panel (figure 5.5). The air flows were as shown in figure 1.1 - exhaust innermost and fresh air outermost. In figure 5.5 the exhaust air is led to the lower duct while the fresh air is coming in through the upper duct.

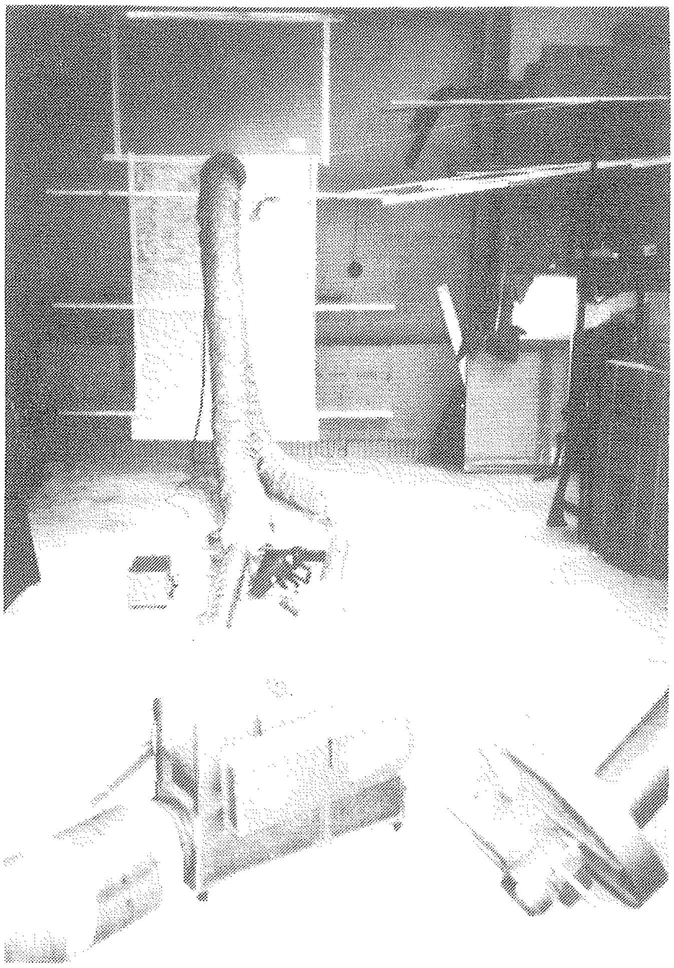

Figure 5.4 The test arrangement for test of the MF-panel as heat exchanger.

As in the test of the MF-panel as solar collector the 'measuring ducts' with thermocouples and a thermopile were used for measuring the inlet and outlet temperatures and temperature difference across the panel for fresh air. The inlet air temperature of the exhaust air was measured by 7 thermocouples connected in such a way that they gave one mean temperature. These thermocouples were placed in a small piece of duct so every thermocouple measured the temperature of equal areas of the cross section of the duct - see figure 5.6.

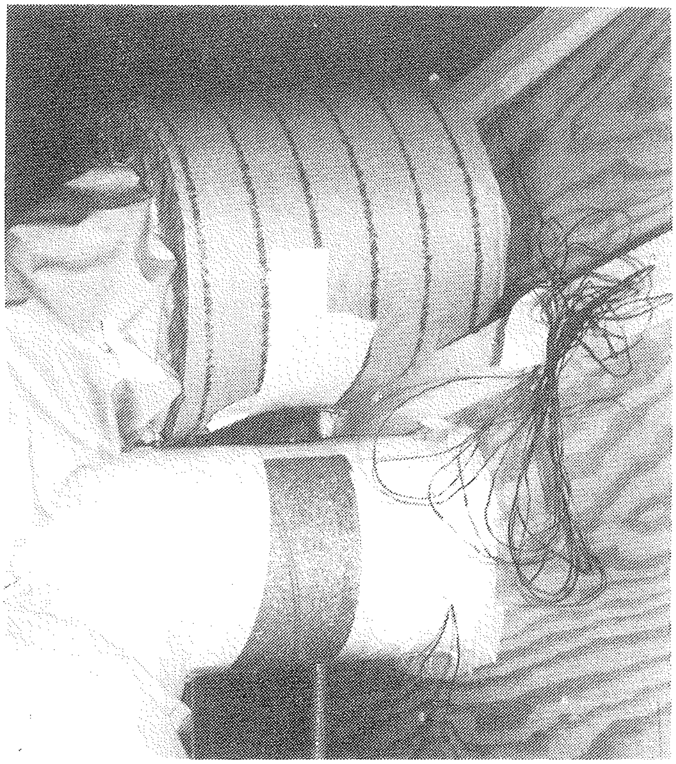

Figure 5.5 The inlet and outlet to the MF-panel.

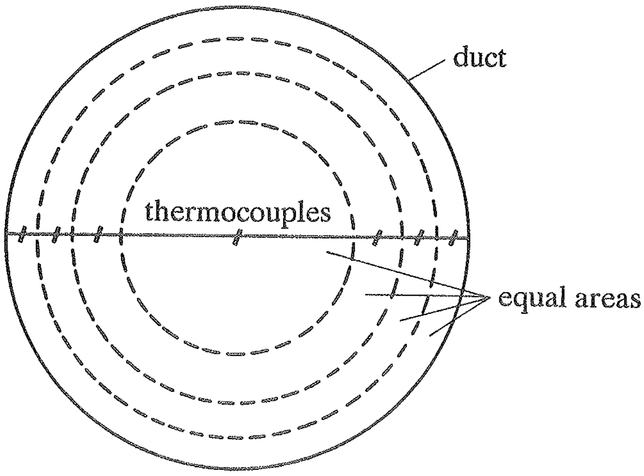

Figure 5.6 The arrangement of the thermocouples in the inlet to the MF-panel of exhaust air.

Figure 5.7 shows the measuring equipment used for the test.

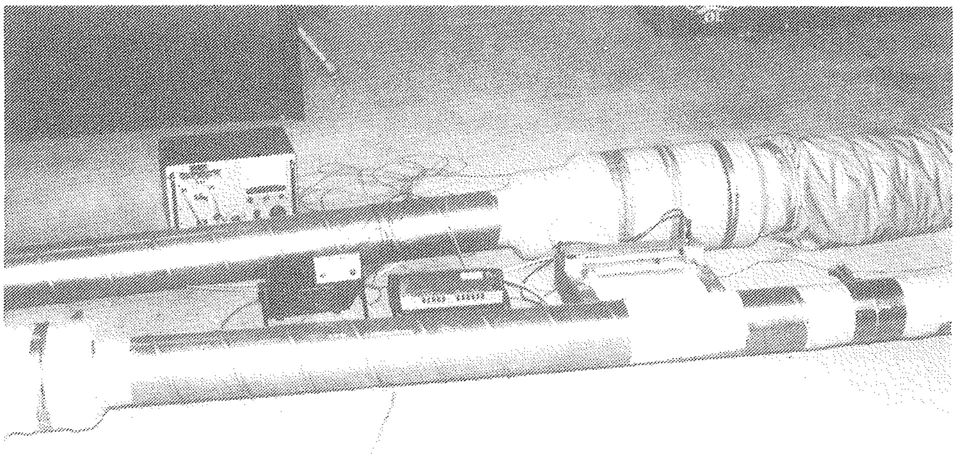

Figure 5.7 The measuring equipment.

5.2 Results from the efficiency tests

The efficiency of the MF-panel acting purely as a heat exchanger was found using the following equation:

$$\eta = \frac{v_f \rho_f c_{pf} \Delta T}{v_e \rho_e c_{pe} (T_o - T_a)} \tag{5.1}$$

where: the subscripts f and e stand for fresh air and exhaust air,
v is the flow rate through the MF-panel [m³/h],
ρ is the density [kg/m³],
c_p is the heat capacity [J/kgK],
ΔT is the temperature difference of the fresh air across the MF-panel [K],
T_o is the inlet temperature of the exhaust air to the MF-panel [K],
T_a is the ambient temperature = the inlet temperature of fresh air [°C].

In figure 5.8 the results from tests of the MF-panel with the transparent cover are shown. The first result was obtained at 5.25 p.m. and the last at 10.20 p.m. During more than half the measurements the panel was influenced by solar irradiation. The results with and without solar irradiation on the panel are dispersed over the whole interval of flow rates. This is done to see if it was possible to account for the solar irradiation. Solar irradiation has been accounted for in the following way: The panel was facing eastwards, which means that after 12 noon the panel was only exposed to diffuse radiation. The solar irradiance was measured by a pyranometer, as shown in figure 5.1 and 5.2. The results from the test of the MF-panel as solar collector were then used. Using the flow rate as entry, the efficiency of the solar collector was calculated and corrected for the fact, that the incidence angle of the radiation was not perpendicular to the cover of the panel. As seen in the next chapter it is possible to account for this by using an incidence modifier angle and using the normally accepted assumption that the mean incidence angle of diffuse radiation is 60°. This gives a correction factor of 0.72 (see chapter 6). The corrected solar input was then simply deducted from the measured heat gain of the MF-panel. This could be done because the solar input was small compared to the heat gain from the heat exchanger, the solar input will of course influence the heat exchange between the two air flows as the solar input is supplied (for the MF-panel with a transparent cover) to the wall between the two air flows. The wall will be heated by the sun and thereby influence the heat exchange between the two air flows - this will be discussed in chapter 6. In figure 5.8 the results are shown indicating how much solar input there has been accounted for in the correction procedure. This is shown as a percentage of the heat gain from the heat exchanger.

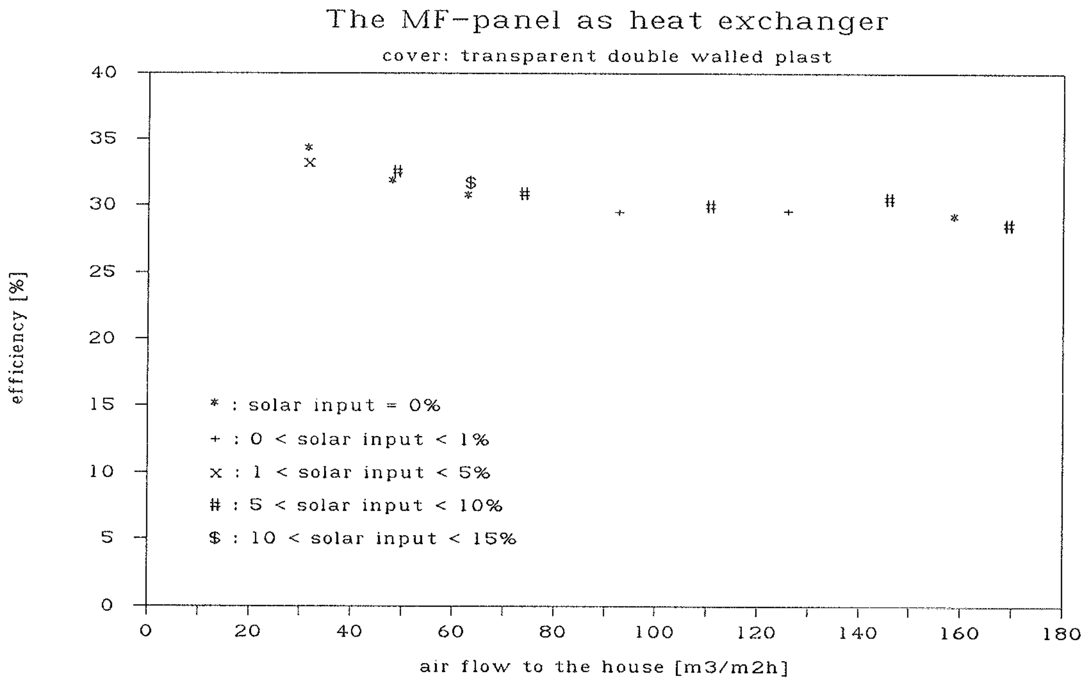

Figure 5.8 The efficiency of the MF-panel with a transparent cover working as a heat exchanger between the fresh air and the exhaust air. The efficiency is corrected for solar input.

From the figure it seems, that at least for small solar inputs it is possible to account for the solar input in the above described way. Figure 5.8 further shows that the efficiency is only modestly influenced by the flow rate through the panel.

Figure 5.9 shows the results from tests performed on the MF-panel with the metal sheet as cover. These tests have all been performed after sunset, so there is no solar irradiation to account for. The results are shown according to the magnitude of the gust of wind.

Figure 5.9 indicates that the magnitude of the gust of wind does not influence the performance of the heat exchanger. This further indicates that the heat loss through the cover is very small. This is illustrated in figure 5.10 where the results shown in figure 5.8 and 5.9 are shown together. There is no significant difference between the efficiency of the MF-panel with two different covers.

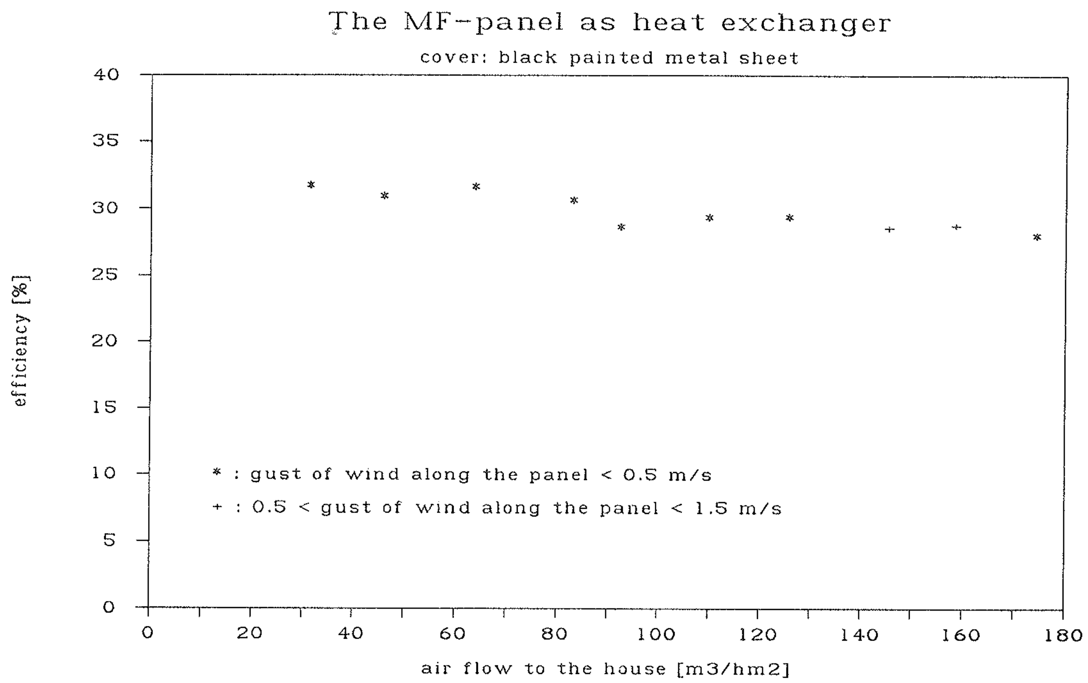

Figure 5.9 The results from tests of the MF-panel with a metal sheet as cover working as a heat exchanger between fresh air and exhaust air.

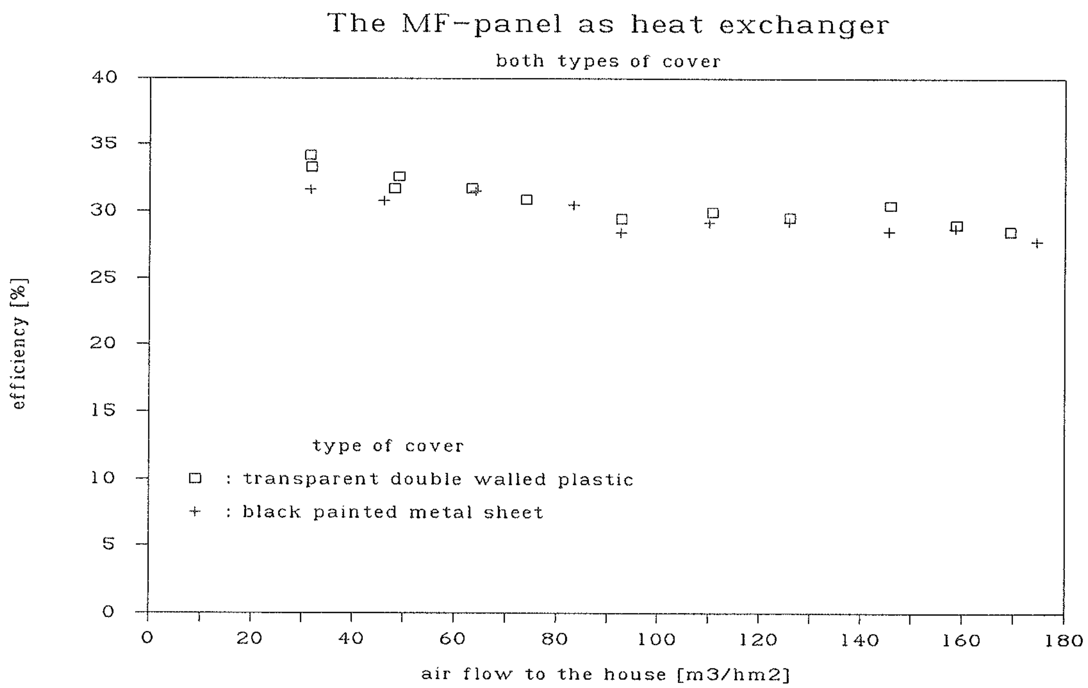

Figure 5.10 The results from tests of the MF-panel working as a heat exchanger with both types of covers.

In order to investigate how important the influence of the heat loss through the cover really is, some calculations have been carried out. The heat loss through the cover has been calculated in the following way: The heat transfer coefficient between the fresh air and the inside of the cover corresponds to the coefficient calculated in section 5.6 (see this). The outside heat transfer coefficient is calculated using the following formula:

$$h_0 = 5.7 + 3.8\,v \tag{5.2}$$

where: v is the speed of the wind along the outside surface of the cover (Duffie et al, 1974).

The gust of wind along the cover was measured during the test, the measured values are used here. For the MF-panel with the transparent cover the gust of wind was between 0.5 and 2.5 m/s, for the MF-panel with the metal sheet the gust of wind was between 0.5 and 1.5 m/s. For the conduction through the cover the following values have been used: Metal sheet: λ-values = 50 W/mK and thickness of the sheet = 0.01 m. Transparent cover: U-value = 3.2 W/m^2K which is similar to the one for a window (Dansk Ingeniørforening, 1977). The basis for the calculations is the measured values for the MF-panel with transparent covers without solar input.

The results of these calculations are shown in figure 5.11. On the basis of the calculated heat loss through the two types of covers it has been estimated how large the efficiency difference between the two types of covers should be. The figure also shows the measured differences. It can be seen that the estimated differences are 2-3 times higher than the measured differences. This can be due to the rather important uncertainty of the calculations and the measurements, but it can also indicate that the heat loss is really lower than calculated. If the boundary layer between the flow of fresh air and the inside of the cover does not participate in the heat transfer process between the fresh air and the exhaust air it will hardly be heated and the temperature of the fresh air will be almost identical to the ambient temperature; the heat loss will, therefore, be very small.

If the small influence of the front heat loss is caused by the boundary layer, the influence of this heat loss may increase if the MF-panel is not mounted vertically eg on a roof. It has not been possible to investigate this problem within the project.

Figure 5.12 shows the results from tests where the ratio between the flow rate of fresh air and exhaust air has been varied. These tests show that the performance can be increased by about 10% when having identical flow rates on both sides. On the other hand, the performance will decrease if the ratio between the flow rates is increased.

The results shown in figure 5.8-10 are obtained for the prototypes described in chapter 3. The question is now, will the efficiency change if the dimensions of the panel are changed, say, if the panel is made longer? This will be discussed in section 5.6.

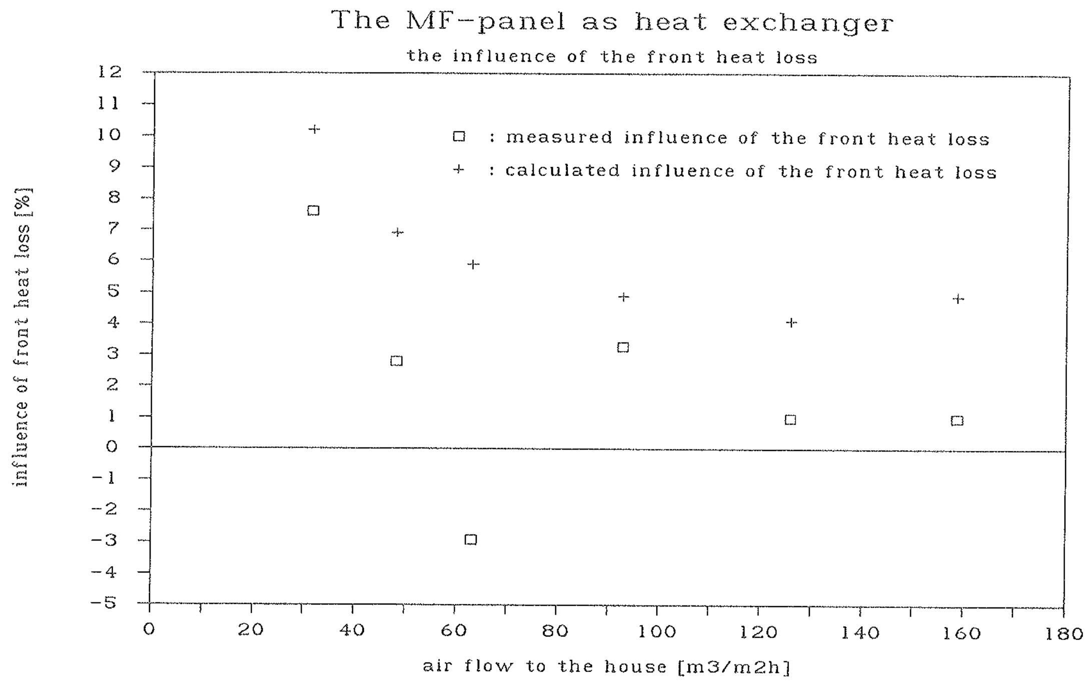

Figure 5.11 The influence of the heat loss through the cover. The influence is shown as the measured and calculated differences between the efficiencies of the two types of MF-panels.

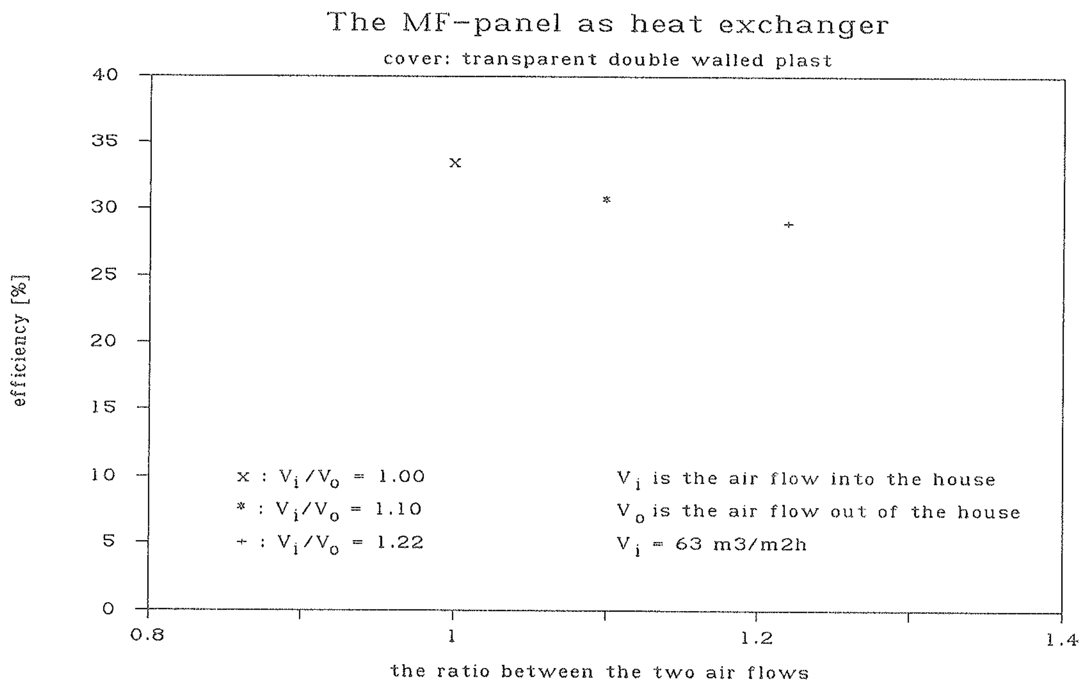

Figure 5.12 Results of varying the ratio between the two flow rates through the MF-panel working as a heat exchanger.

5.2.1 Uncertainties

Figure 5.10 shows the measured efficiencies of the MF-panel working as a heat exchanger. The question is, however, how well these efficiencies are determined. To answer this question the uncertainties of the measured efficiencies have been calculated.

The uncertainties are found from the uncertainties on the measuring equipment. Only the six main uncertainties have been considered. These uncertainties are:

Two Fläkt flow measuring devices: 5%
Two Micro manometers: 0-12.5 mmhg (0-400 m^3/h) : 0.125 mmhg
12.5-25 mmhg (400-564 m^3/h) : 0.25 mmhg
Temperature difference fresh air: 0.3 °C.
Temperature difference exhaust air: 0.5 °C.

It is assumed that these six uncertainties are independent. The law of accumulation can, therefore, be used. The uncertainty of the measurements is therefore - knowing that to find the flow rate it is necessary to extract the square root of the pressure drop (Δp) across the flow measuring device.

$$\frac{s(\eta)}{\eta}=\sqrt{2(\frac{1}{2}0.05)^2+(\frac{1}{2}\frac{s(\Delta p_f)}{\Delta p_f})^2+(\frac{1}{2}\frac{s(\Delta p_e)}{\Delta p_e})^2+(\frac{s(\Delta T_f)}{\Delta T_f})^2+(\frac{s(\Delta T_e)}{\Delta T_e})^2} \qquad (5.3)$$

where: f and e stand for fresh air and exhaust,
Δp is the pressure drop across the flow measuring device [Pa],
ΔT is the temperature difference across the MF-panel [K].

In figure 5.13 the calculated uncertainties of the efficiencies of the MF-panel with the transparent cover are shown. The uncertainties are shown as full lines in order to make the figure more clear. The uncertainties of the other configuration of the MF-panel show a similar picture.

For flow rates higher than 60 m^3/m^2h the uncertainties are very well determined. The uncertainties are here between ±7 and ±9%. For very high flow rates (>180 m^3/m^2h) the uncertainty begins to increase. This is caused by the fact that the temperature difference across the collector becomes so low that the uncertainties of the temperature difference begin to become dominant.

5.3 Pressure drop

When the MF-panel was still mounted at the experimental house the pressure drop across the panel was measured. The results of these measurements are shown in figure 5.14. Two curves are shown for the exhaust: For the curve entitled "exhaust 1" both the inlet to and the outlet from the panel were reduced to half the area of the cross section between the trapezium corrugated metal sheet and the insulated wall (fig. 3.4) (the MF-panel was tested with this configuration), for the curve titled "exhaust 2" only the inlet to the MF-panel was reduced to half the area of the cross section (see also paragraph 3.2).

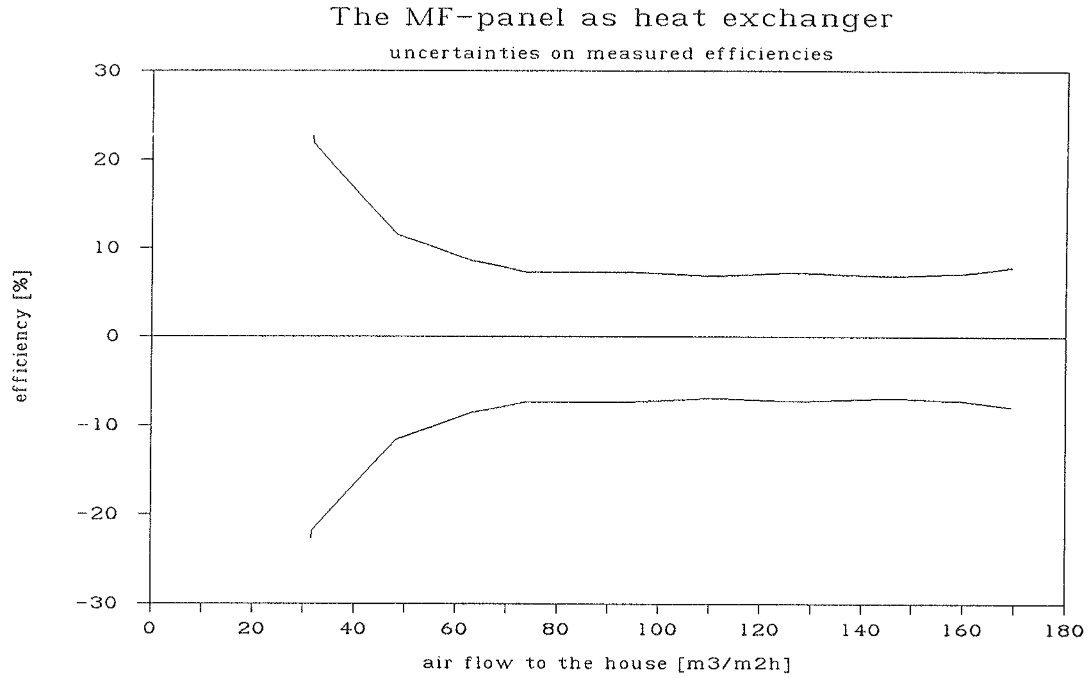

Figure 5.13 The uncertainties of the efficiencies of the MF-panel with the transparent cover and no wind.

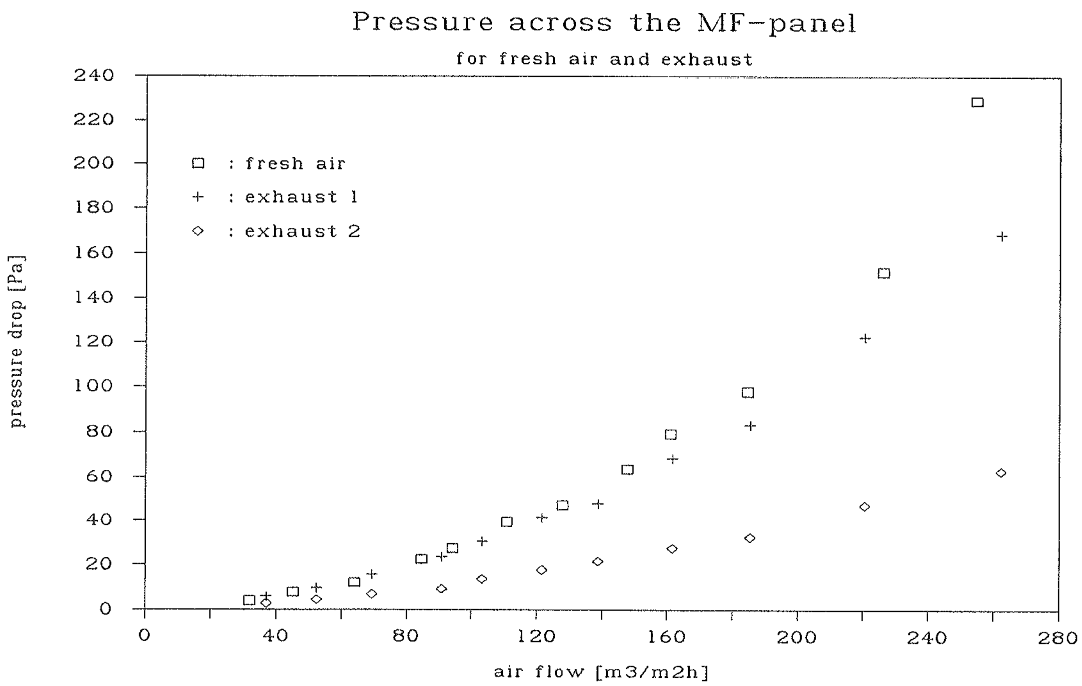

Figure 5.14 Pressure drop across the MF-panel.

From measurements of the air speed at the inlet of fresh air to the panel it is believed that the pressure drop across the panel is sufficient to maintain a uniform flow rate over the complete cross section.

5.4 Heat loss

The exhaust air from the house is let down along the outside of the insulated wall. This means that the wall during the heating season is exposed to a higher air temperature than a normal wall, which is exposed to the ambient air temperature. This will decrease the heat loss through the wall, but how much? Two examples will illustrate this.

As shown in chapter 3 - figure 3.2 and 3.3 - the wall consists of 100 mm insulation and laths between 12 mm plywood. Between the plywood, 91.5% of the space is filled with insulation, the rest is filled with laths. The mineral wool is mounted at the site and is assumed to have a λ-value of 0.039 W/mK while the laths has a λ-value of 0.12 W/mK (Dansk Ingeniørforening, 1977). The mean U-value for the insulated wall is therefore 0.41 W/m^2K. According to the Danish Building Regulations the U-value for a light weight wall should not exceed 0.3 W/m^2K (The Danish Ministry of Housing, 1983).

The area of the insulated wall is 2.21 m^2. The manifolds are not insulated to the same extent as the insulated wall, and they are not even insulated in order to prevent heat loss. The heat loss to the upper manifold is led to the fresh air, which is blown into the house, so there is no real heat loss here. There is no heat loss to the lower manifold as the exhaust air enters here, and therefore it will have the same temperature as the house. For the MF-panel we will, therefore, only have to consider the heat loss through the insulated wall of 2.35 m^2 even if the area of the MF-panel is 3.05 m^2.

5.4.1 Example of the measurements

The example is from April 13, 1989 at 9.40 p.m. The measurements are carried out for the MF-panel with the transparent cover. Table 5.1 shows the measured values used for the example.

Ambient temperature	4.1 °C
Temperature of the exhaust air	22.2 °C
Temperature of the pre-heated fresh air	10.1 °C
Temperature of the room	20.8 °C
Flow rate of the fresh air	63 m^3/m^2h
Energy contents of the exhaust air	1470 W
Energy supplied to the fresh air	456 W

Table 5.1 The measured values used for the example.

From figure 5.8 it is seen that the efficiency of the heat exchanger is 31%. The temperature of the exhaust air leaving the MF-panel is therefore 16.6 °C, and the mean temperature of the exhaust air in the MF-panel is 19.4 °C, which means that the insulated wall is exposed to a 15 K higher temperature than a normal wall.

The heat loss through the two walls is in this example:

Normal light weight wall $0.3 \cdot 3.05 \cdot (20.8-4.1) = 15.3$ W

The wall in the MF-panel: $0.41 \cdot 2.35 \cdot (20.8-19.4) = 1.35$ W

The heat loss through the wall is in this way reduced to 8.8%. But 31% of the heat loss through the insulated wall in the MF-panel is transferred to the fresh air, so the heat loss is really reduced to about 6%.

From this example it is seen that the heat loss through the panel does not influence the measurements as the heat loss is smaller than 1% of the energy contents of the exhaust air.

5.4.2 Design case

In Denmark heating systems are normally designed for a case with an ambient temperature of -12 °C and no solar irradiation. Let us examine the reduction of the heat loss in this case. In table 5.2 the input parameters of the example are shown.

Ambient temperature	-12 °C
Temperature of the exhaust air	20 °C
Temperature of the room	20 °C
Flow rate of the fresh air	65 m^3/m^2h

Table 5.2 The input data used for the design case.

In this case the outlet temperature from the MF-panel of the exhaust air is 10.1 °C, and the mean temperature of the exhaust air in the MF-panel is 15.1 °C.

The heat loss from the two walls is now:

Normal light wall $0.3 \cdot 3.05 \cdot (20-12) = 29.3$ W

The wall in the MF-panel: $0.41 \cdot 2.35 \cdot (20-15.1) = 4.7$ W

In this case the heat loss is reduced to 16%, but if only 31% of the heat loss through the insulated wall of the MF-panel is transferred to the fresh air, the heat loss is reduced to about 11%.

These two examples show how much the heat loss through the wall is reduced during, say, night time. When there is solar irradiation at a normal wall the surface of the wall will often be heated to a higher temperature than the ambient air temperature, and sometime also to a higher temperature than the wall in the MF-panel is exposed to. In order to find the annual reduction of the heat loss through the MF-panel simulations must be made. It has not been possible to perform such simulations within the frame of this project.

5.5 Condensation

In a MF-panel heat is exchanged between warm, maybe humid air and cold air. This means that it is possible that some of the humidity of the exhaust air will condense on the trapezium corrugated metal sheet. This will increase the heat exchange between the two air flows as a lot of energy is released when water changes phase from gas to liquid.

In this paragraph very simplified calculations will be performed in order to investigate the expected energy gain, due to condensation. The calculations are based on the following simplified assumptions: It is assumed that the cooling of the exhaust air is uniform (which is not possible in the duct profile of the MF-panel). It is further assumed that the condensation does not change the heat transfer between the two air flows (the condensation of water will increase the temperature of the wall between the two flows and thereby decrease the dry heat exchange between the two flows and also further reduce the condensation). This means eg that less energy than found from the following calculations is actually transferred.

The calculations are performed for the case of a flow of fresh air to the house of 65 m^3/m^2h and a temperature of the exhaust air of 20 °C. It is assumed that the heat loss through the cover can be ignored. The heat transfer between the two air flows is 31%. The water will condensate on the wall between the two air flows which means that the efficiency of the heat exchange to the fresh air is 62%.

For the calculation of the decrease of the water contents of the exhaust air, when passing through the MF-panel, the simple formula from Nielsen (1982) has been used.

The results of the calculation for different relative humidities of the exhaust air and different ambient temperatures are shown in table 5.3.

In table 5.4 the same calculated transferred energy due to condensation (as in table 5.3) is shown as a percentage of the amount that would have been transferred if no condensation had occurred.

As already mentioned, it has neither been considered that the condensation will decrease the dry heat transfer between the two air flows, nor that the wall between the two air flows will be heated up due to the condensation and thereby decrease the amount of water that will condensate.

The tables can, however, give an idea of when condensation will occur and how much it will influence the overall heat transfer: It is not likely that condensation will take place if a MF-panel is installed in a residential building where the normal relative humidity of the indoor air is about 60% and even lower during winter time with ambient temperatures below 0 °C. If MF-panels are installed in industrial buildings with a high relative humidity of the indoor air, condensation can increase the performance of the MF-panels considerably. If condensation occurs, it is necessary to ensure that the condensate is led away without damaging the panels or the building.

ambient temperature	indoor relative humidity %			
°C	40	60	80	100
15	0	0	0	52
10	0	0	0	101
5	0	0	34	146
0	0	0	71	183
-5	0	0	108	220
-10	0	30	142	254
-15	0	60	172	284
-20	0	90	202	313
dew point temperature	6.2 °C	12.1 °C	16.5 °C	20 °C

Table 5.3 The energy transferred (W/m^2) to the fresh air due to condensation and the dew point of the exhaust air.

5.6 Theory

In this project, is has not been possible nor been the aim to develop a theory for prediction of the heat transfer occurring within a MF-panel. A first attempt has, however, been performed in order to see if it was possible to make an estimate of the performance of the MF-panel working as a heat exchanger.

It is a non trivial task to describe a heat exchanger theoretically. It has, therefore, been chosen to use a rather simple method - the NTU method (Pitts et Al, 1977). Using the NTU method it is possible to predict the performance of several different types of heat exchangers including a counter flow heat exchanger (single pass) as a MF-panel.

$$\eta = \frac{1-\exp[-NTU(1-C)]}{1-C\exp[-NTU(1-C)]} \tag{5.4}$$

$$NTU = \frac{UA}{C_{min}} \tag{5.5}$$

ambient temperature	indoor relative humidity %			
°C	40	60	80	100
15	0	0	0	133
10	0	0	0	131
5	0	0	29	126
0	0	0	46	118
-5	0	0	56	114
-10	0	13	61	109
-15	0	22	63	105
-20	0	29	65	101

Table 5.4 The energy transferred due to condensation shown as the percentage of the energy transferred if no condensation had occurred.

$$C = \frac{C_{min}}{C_{max}} \qquad (5.6)$$

where: U is the heat conductivity between the two flows [W/m²°K],
A is the heat transferring area between the two flows [m²],
C is the mass flow rate for the flows [kg/s], and min and max stand for the highest and lowest mass flow rates.

U is found from:

$$U = \frac{1}{\frac{1}{h_f} + \frac{t}{\lambda} + \frac{1}{h_e}} \qquad (5.7)$$

where: h is the heat transfer between the air and the wall [W/m²°K], e and f stand for exhaust air and fresh air,
t is the thickness of the wall separating the two air flows, e is here 1 mm,
λ is the conductivity of the wall separating the two air flows, λ is here 50 W/m°K.

h_f and h_e are found from (Saustrup Kristensen, 1978):

$$h = \frac{Nu\,\lambda}{L} \qquad (5.8)$$

$$Nu = 0.46\,(Re\,Pr)^{0.65} \qquad (5.9)$$

where: Nu is the Nusselt's number,
λ is the conductivity of the air [W/m°K],
L is the characteristic length, here the length of the heat transferring area = 2.03 m,
Re is the Reynolds' number for the air,
Pr is the Prandtl's number for the air.

The equation is only valid for Pr << 1 and $10^3 < Re \cdot Pr < 10^5$, but Pr is here about 0.7 and Re·Pr is in most cases above 10^5. The formula has, however, been chosen because it gives the highest heat transfer coefficients, which is needed as shown later.

Using the above described formula it has been tried to predict the efficiency of the MF-panel working as a heat exchanger. The chosen cases are the measured situations from figure 5.8. Only the cases without solar input have been used.

Figure 5.15 shows the comparison between the measured and predicted efficiencies of the MF-panel working as a heat exchanger. In the figure the uncertainties of the measurements are also shown. The uncertainties are shown as full lines just to make the figure more clear.

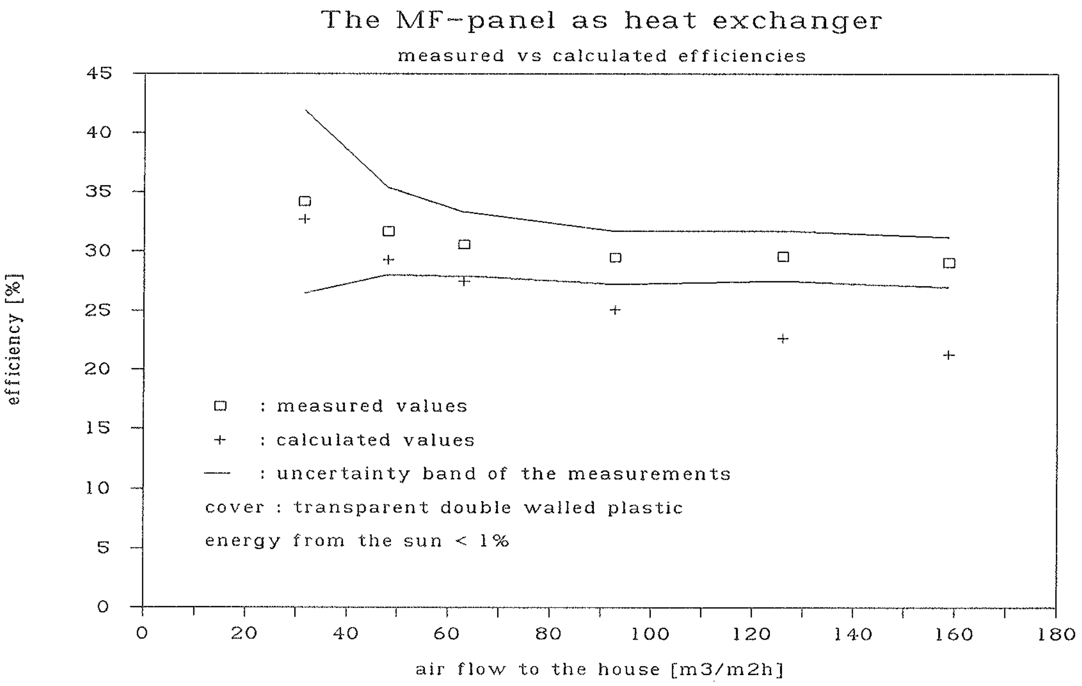

Figure 5.15 Measured and predicted efficiencies of the MF-panel working as a heat exchanger.

It is only for small flows (< 60 m^3/m^2h) that the predictions agree with the measurements. For higher flows the formula predicts a far too low efficiency. This can be caused by the fact that the surface of the wall separating the two air flows is not smooth as assumed by the formula, but rough. This increases the turbulence along the surface and thereby the heat transfer. The formula further assumes that the temperature of the wall is constant all over the wall. In a counter flow heat exchanger this temperature of course varies down along the wall. Another possible reason for the difference is a shortcut between the two air flows. If the trapezium corrugated metal sheet is not sealed properly, exhaust air will be mixed with the fresh air causing a higher measured efficiency. The influence of the shortcut will further increase with increasing flow rate due to increased pressure difference between the two flows.

Even if the described theory does not predict the same efficiency as the measurements the theory will be used to investigate how a change of the dimensions of the MF-panel will influence the efficiency. It is to be hoped that the theory shows a similar trend as the measurements would have done.

Using the theory the efficiency of the situations shown in figure 5.15 have been calculated - the only change is that the panel is twice as long as the prototypes. The width, flow rate per m^2 and all other parameters are identical to those of the test. The calculations show that the efficiency will increase by 18% for the situations shown in figure 5.15 - the increase is independent of the flow rates. The increase of efficiency is caused by two things: 1) The total flow rates in the panel are doubled up, while the cross sections of the ducts in the panel are identical. The air speed is therefore increased causing a higher heat transfer between the absorber and the air. 2) In the prototypes the heat transferring area between the two air flows is only 87% of the area of the trapezium shaped sheet due to the upper manifold which does not take part in the heat transfer process. For a MF-panel with double length, the manifolds will not be larger, so the heat transferring area will be 94% of the area of the trapezium corrugated metal sheet.

Even if we cannot say for certain that the trend of the model is the same as it would be in real life, we can conclude that there is a possibility for increasing the performance of the MF-panel by making the panel longer. But when making the panel longer the pressure drop across the panel will also increase and lead to increasing power demand for the ventilators. An optimization process is necessary in order to find the optimal length of a MF-panel.

The above described example shows as well as the example in section 4.3 that further work is necessary in order to establish a theory for prediction of the efficiency of the MF-panel. A theory of this kind is necessary for optimization the MF-panel.

6 Annual performance of the MF-panel

In the previous chapters the performance of two prototypes of MF-panels working purely as a solar collector and purely as a heat exchanger for preheating of fresh air, have been investigated. The efficiencies have been measured and different processes, which may influence the efficiencies, have been discussed. This, however, does not give an impression of the performance of a MF-panel installed in a real building. The annual performance is highly dependent of parameters like the solar irradiation, ambient temperature and heat demand. In order to establish a knowledge of the annual performance, simulations will have to be made using real weather data and heat demands corresponding to the chosen weather data.

6.1 Weather data and heat demands

The following simulations have been carried out using the Danish Test Reference Year (TRY) (Statens Byggeforsknings Institut, 1982). This data base contains typical Danish weather data selected out of 15 years measured weather data. The data consist of hourly values of, say, the ambient temperature, global and diffuse solar radiation on a horizontal plane, wind direction, wind speed, relative humidity.

As heat demand it was decided to use a data base containing hourly heat demands for an old and a new (BR-82) single family house. The houses have a built up area of 140 m^2. The new house is insulated according to the Danish standards for insulation - BR-82 (The Danish Ministry of Housing, 1983). The heat demand shown in table 6.1 is the net heat demand. The net space heat demand is the gross space heat demand minus the utilized free heat gain from persons, electric appliances and the solar irradiation through windows (Lawaetz, 1977).

These two houses were chosen because the data are prepared specifically for simulations and therefore easy to use. Another reason for choosing these data was, as shown in table 6.1, to investigate the MF-panel for a range of heat demands. In order to see the influence of a heat demand during the summer-time simulations were performed for both houses with and without a heat demand during the five summer months - May-September. The heat demands per month for the four houses are shown in figure 6.1-6.4.

Type of house	Net space heat demand	
	summer demand kWh/year	no summer demand kWh/year
Old house	23,800	20,600
BR-82 house	14,100	12,400

Tabel 6.1 The heat demands used for the simulations.

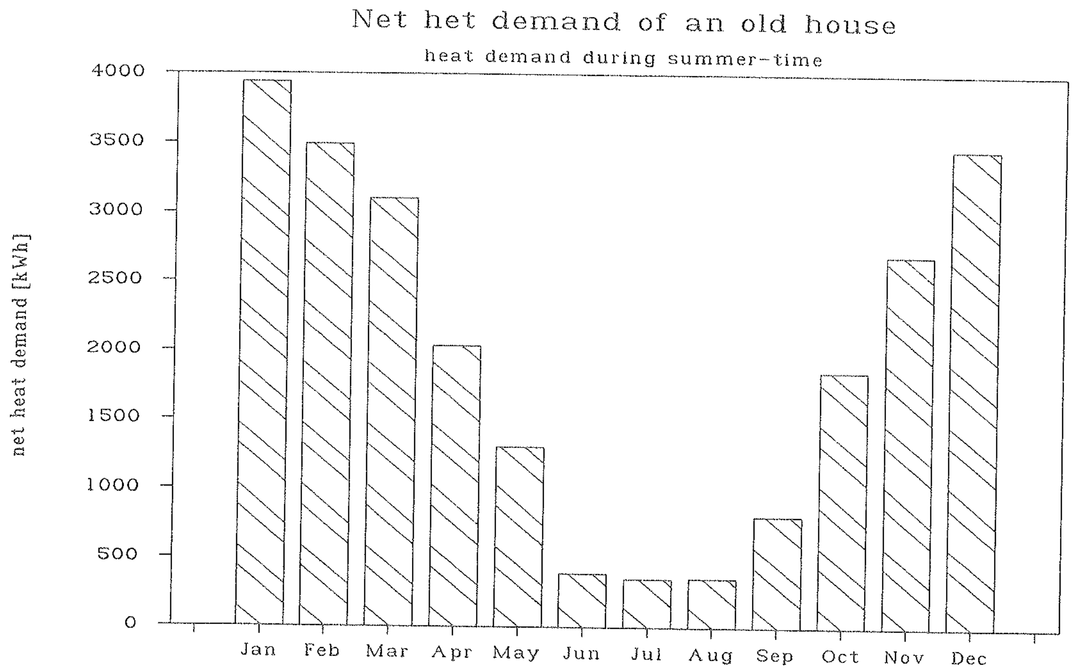

Figure 6.1 Heat demands per month for an old house with heat demand during summer-time.

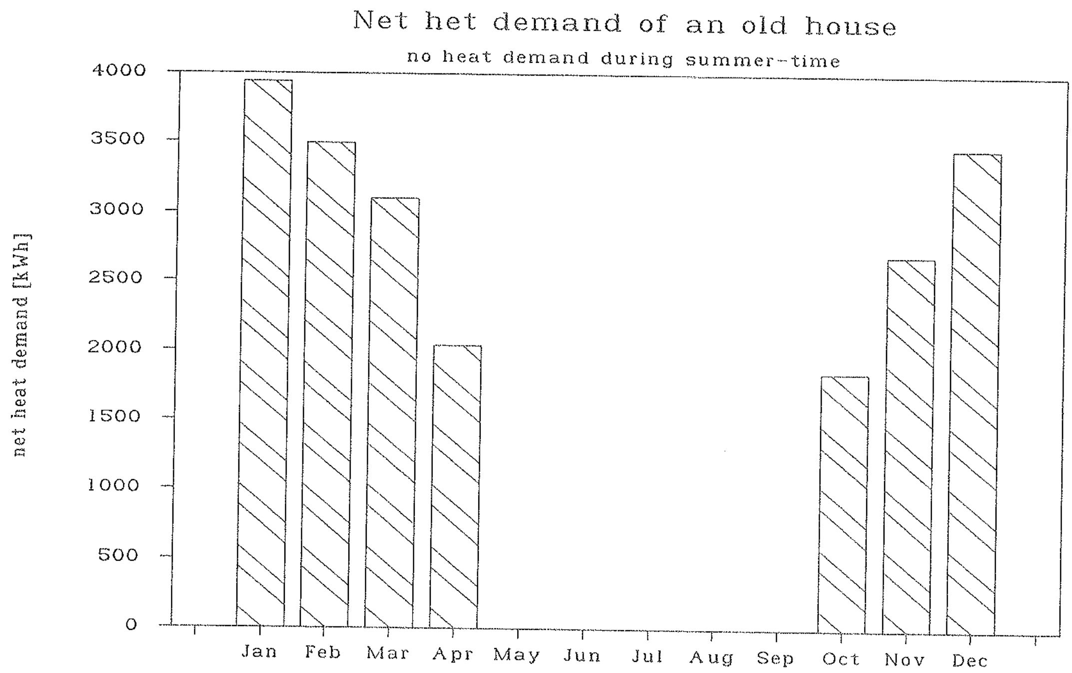

Figure 6.2 Heat demands per month for an old house with no heat demand during summer-time.

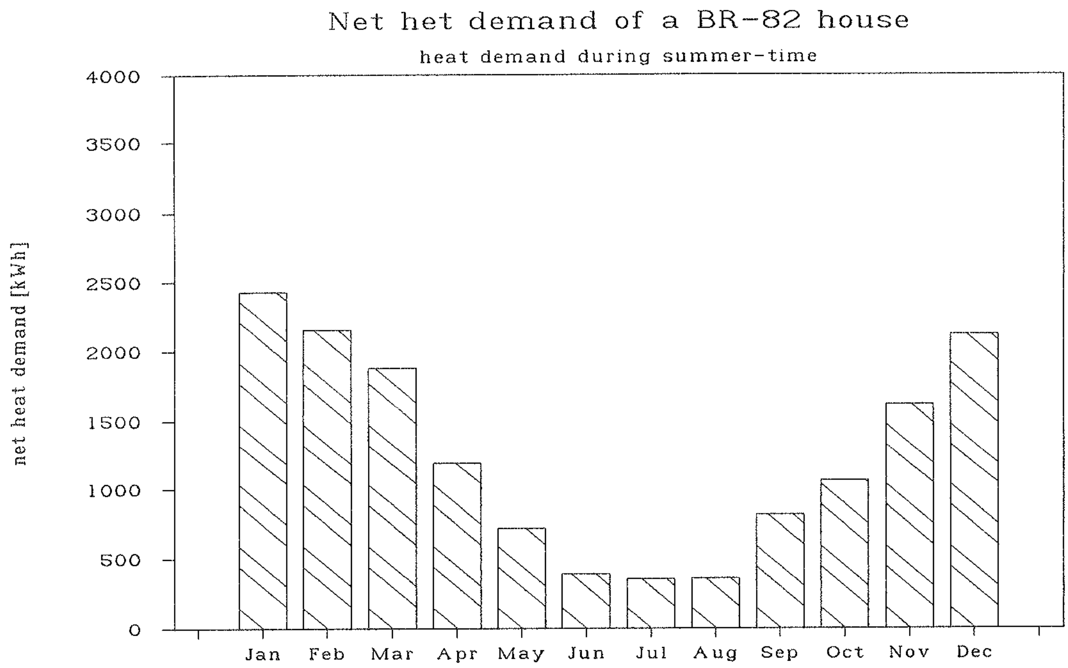

Figure 6.3 Heat demands per month for a BR-82 house with heat demand during summer-time.

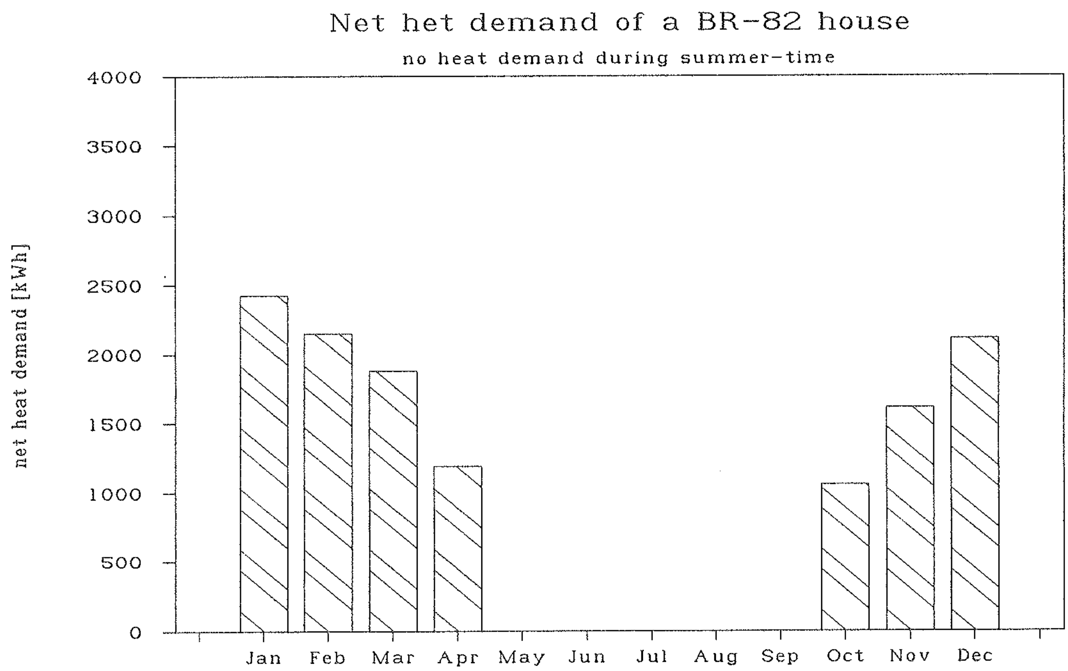

Figure 6.4 Heat demands per month for a BR-82 house with no heat demand during summer-time.

The ventilation rate for the two houses is 0.65 air changes per hour for the old house and 0.4 air changes per hour for the new house (Lawaetz, 1977). The air flow rate of fresh air is then 198 m^3/h for the old house and 122 m^3/h for the new house (the flow rate of exhaust air is 10% higher than the flow rate of fresh air).

6.2 Simulations

On the basis of tests of the two prototypes it was decided only to perform simulations for the best performing prototype - the MF-panel with a transparent cover.

In the test of the MF-panel as solar collector the incidence angle of the irradiation was perpendicular to the plane of the cover of the MF-panel. This situation occurs, however, very seldom in reality due to the movement of the sun. The efficiency of the MF-panel acting as solar collector depends largely on the incidence angle of the irradiation (see figure 7.1), it is therefore important to account for the incidence angle in the simulations. To account for the incidence angle the incidence angle modifier method has been used (Duffie, 1974).

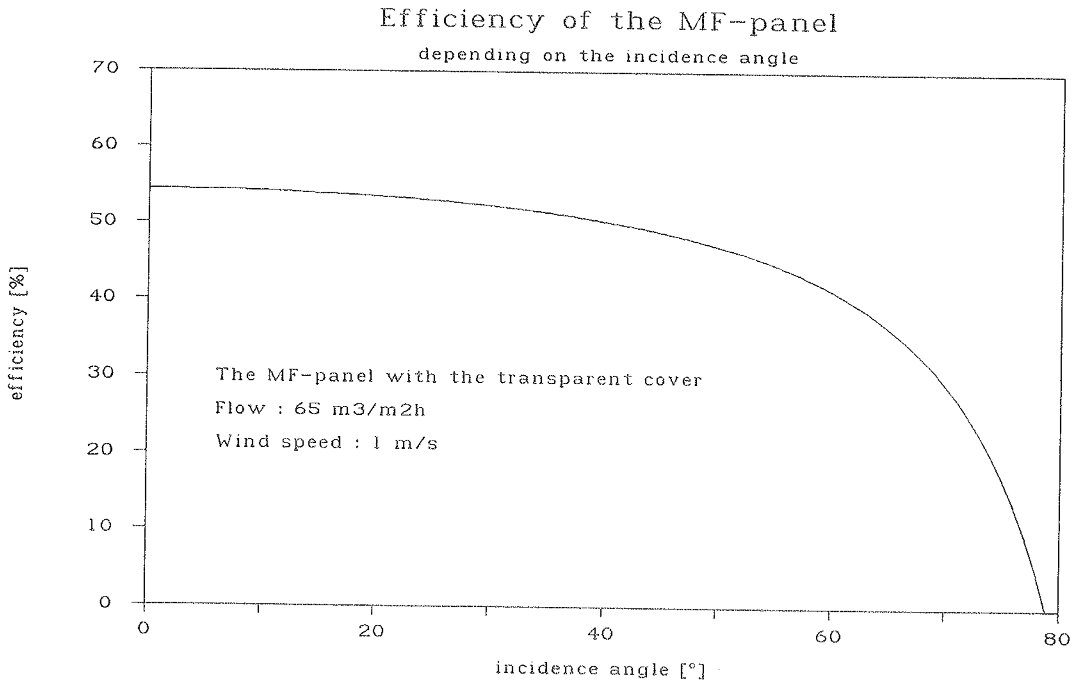

Figure 6.5 The influence of the incidence angle of the solar irradiation on the efficiency of the MF-panel with the transparent cover.

The incidence angle modifier ($K_{\tau\alpha}$) is the ratio between the actual transmittance-absorptance product ($(\tau\alpha)$-product) of the cover (for the actual incidence angle of the irradiation) and the ($(\tau\alpha)_n$-product) of the cover when the irradiation is perpendicular to the cover. The incidence angle modifier is defined as:

$$K_{\tau\alpha} = \frac{(\tau\alpha)}{(\tau\alpha)_n} \qquad (6.1)$$

By means of regression, ($K_{\tau\alpha}$) is found to be:

$$K_{\tau\alpha} = 1 + b_0(\frac{1}{\cos\Theta} - 1) \tag{6.2}$$

Where: Θ is the incidence angle of the solar irradiation [°],
For the transparent double walled ribbed acrylic plate b_0 is -0.24 (Østergaard Jensen, 1986b).

The incidence angle modifier is used to correct the solar irradiation on the cover of the MF-panel. After this correction the efficiencies found in chapter 4 can be used directly.

The correction of the incoming solar irradiation is performed in the following way:

$$I_C = I_B K_{\tau\alpha} + I_D K_{\tau\alpha}(\Theta = 60°) \tag{6.3}$$

where: I_C is the corrected global irradiation on the considered plane [W/m2],
I_B is the beam on the considered plane [W/m2] and
I_D is the diffuse irradiation on the considered plane [W/m2], the incidence angle of diffuse radiation is assumed always to be 60°.

6.2.1 Assumptions

In this project the efficiencies of the MF-panel working only as a solar collector or only as a heat exchanger have been measured. It has not been possible, within the project, to investigate the interaction between the solar collector and the heat exchanger. When the MF-panel gains energy from the sun, the energy is supplied to the trapezium corrugated metal sheet through which the heat exchange is taking place. The sun is heating the plate and thereby reducing the heat transfer for small solar inputs. For large solar inputs (larger than what can be gained by the heat exchanger) the plate is cooled by the exhaust air, the efficiency of the solar collector is thereby reduced. How large these reductions are has not been determined, so it is not possible to give an 'exact' answer to the question of the annual performance of a MF-panel installed in a house.

To overcome the above mentioned problem two parallel series of simulations have been performed - an optimistic and a pessimistic one. In **the optimistic series** it is assumed that there is no interaction between the collection of solar energy and the heat exchange - there is no reduction - both air flows are always passing through the MF-panel. In **the pessimistic series** it is assumed that the MF-panel only works either as a solar collector or as a heat exchanger; this means that when the solar input becomes larger than the energy gain from the heat exchanger, the exhaust air by-passes the MF-panel, and when the solar input is small it is not considered.

In the following the pessimistic series is denoted (I) and the optimistic series is denoted (II).

When the energy gain from the MF-panel is higher than the heat demand, the energy gain is reduced to equal the heat demand. For the optimistic series the energy gain from the solar collector and the heat exchanger is reduced so that the ratio between them remains the same as before the reduction.

The indoor air temperature of the houses is assumed to be 20 °C.

The theoretical investigations (section 4.3 and 5.6) have shown that the performance of the MF-panel most probably can be increased by increasing the length of the panel. This has, however, not been taking into consideration in the simulations, partly because it is not certain how large this increase really is, partly because the area of a MF-panel installed in a single family house seldom will be much larger that the prototypes.

As mentioned in section 5.2 the heat loss through the front cover may change if the MF-panel is tilted from vertical. In the simulations this has not been considered. It has also been assumed that no condensation takes place within the MF-panel.

The performance of the MF-panel has been simulated for different orientations and tilts of the panel. As the air flow through the panel is fixed (see section 6.1) the air flow per m^2 has been varied by changing the area of the MF-panel. Table 6.2 shows the efficiencies for the MF-panel as solar collector and as heat exchanger when the area of the MF-panel and thereby the air flow per m^2 was varied. These efficiencies are found from figure 4.6 and 5.8. For the efficiencies of the MF-panel working as solar collector a wind speed of 1 m/s has been used.

air flow of fresh air m^3/m^2h	area of the MF-panel old house m^2	area of the MF-panel BR-82 house m^2	efficiency as solar collector %	efficiency as heat exchanger %
100	1.98	1.22	61	29.5
80	2.48	1.53	58	30
65	3.05	1.88	54	31
50	3.97	2.44	46	32
40	4.96	3.06	40	33
30	6.61	4.07	31	34
20	9.91	6.11	23	35

Tabel 6.2 The efficiencies used for the simulations of the MF-panels working as solar collector and as heat exchanger according to the flow rate.

In the simulations the flow rate of exhaust air was 10% larger than the flow rate of fresh air.

6.2.1.1 Results of the simulations

Several series of simulations have been performed. The results of these simulations are shown graphically in the following. On each page the results of both the pessimistic series (I) and the optimistic series (II) are shown in order to give an impression of the range where the performance of a real system can be found. The intention when performing the large series of simulations is:

1) to make it possible to draw some main conclusions of the performance of the MF-panel,

2) to make it possible to use the results obtained from the simulations as a tool for the design of systems including MF-panels.

Figure 6.6-13 show the performance of the MF-panel depending on the area of the panel (and thereby the flow rate) and the tilt of the panel.

Figure 6.14-21 show the results of similar simulations as shown in figure 6.6-13, but here the performance is shown per m^2 of the MF-panel. This is easier to use than figure 6.6-13 so the rest of the results will be shown in this way.

Figure 6.22-29 show the performance of a MF-panel with a flow rate of 65 m^3/m^2h for different tilts and orientations.

From figure 6.14-21 it is seen that the energy gain from the sun lies between 3 and 25% of the total energy gain from the MF-element - lowest for small areas and no heat demand during summer time, highest for large areas and heat demand during summer-time. This means that it is not that important to optimize the MF-panel as solar collector.

Figure 6.14-21 show that the overall performance (kWh/m^2) of the MF-panel is highly dependent of the area and thereby the flow rate through the panel. The energy gain from the MF-panel is, however, less dependent of the area than the energy gain from the heat exchanger, because the efficiency of the solar collector is increased with increasing flow rate (decreasing area), while the efficiency of the heat exchanger is decreased with increasing flow rate.

From the figures it is seen that the performance of the MF-panel is highly dependent of the heat demand during summer-time. For, say, a flow rate of 65 m^3/m^2h, a tilt of 60° and a south facing orientation, the performance is 15-20% higher (depending of the type of house) for a MF-panel installed in a house with summer demand compared to a house without heat demand during summer-time. The same example shows that there is hardly any difference of the performance of the MF-panel when the energy gain per m^2 for the two different types of houses are compared - the difference is 1.5% for houses without heat demand during summer-time and 4.5% for houses with heat demand during summer-time. This small difference appears because the flows of fresh air to the two houses are adjusted to fit the heat demands of the houses, so the use of these two houses does not really show the range of performance of the MF-panel for different heat demands.

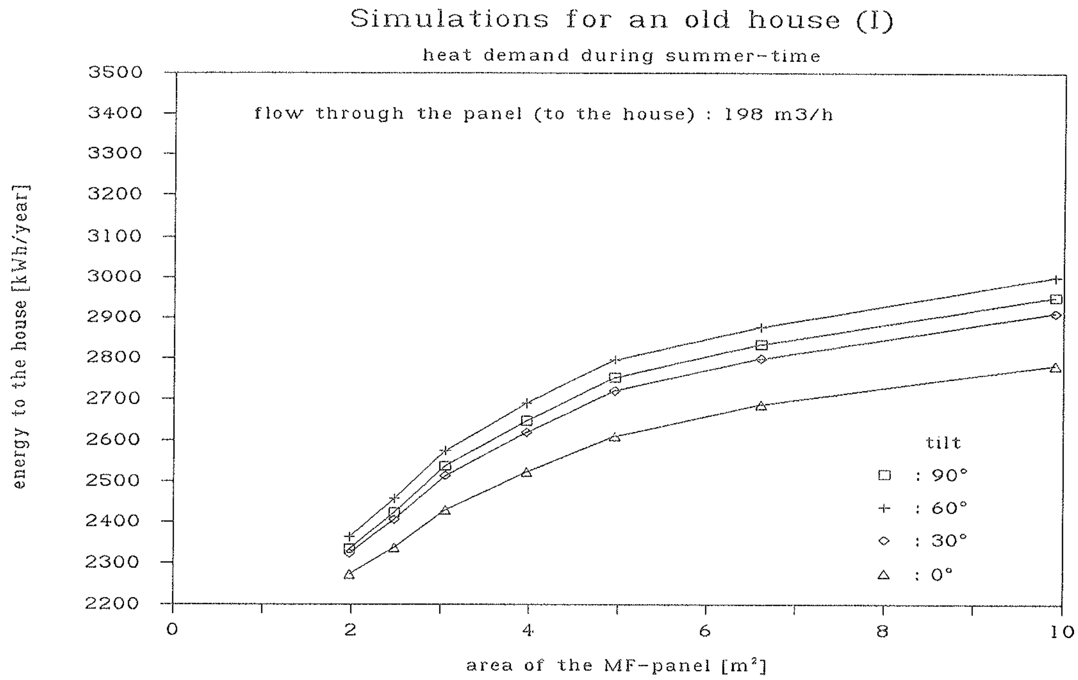

Figure 6.6 The annual performance of the MF-panel installed in an old house with heat demand during summer-time - pessimistic assumptions.

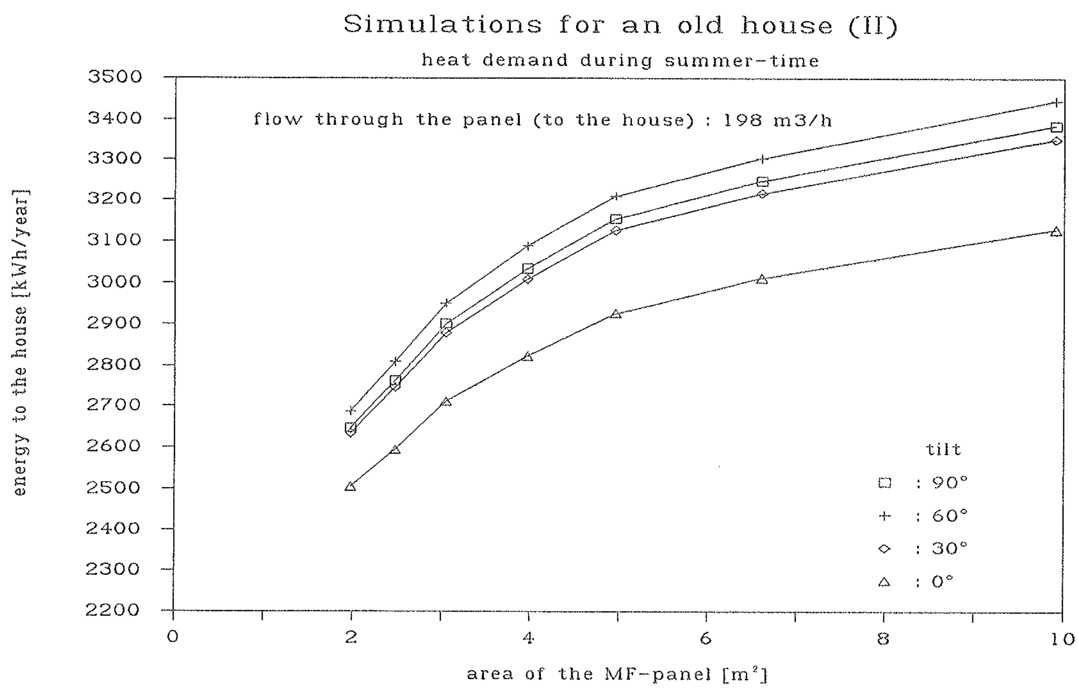

Figure 6.7 The annual performance of the MF-panel installed in an old house with heat demand during summer-time - optimistic assumptions.

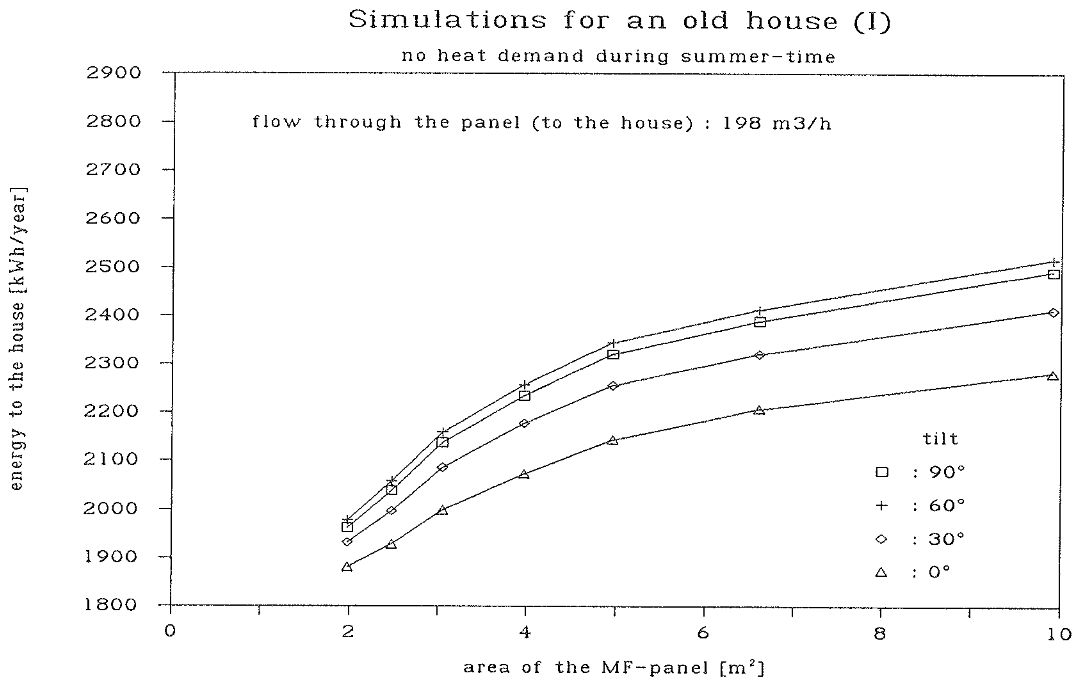

Figure 6.8 The annual performance of the MF-panel installed in an old house with no heat demand during summer-time - pessimistic assumptions.

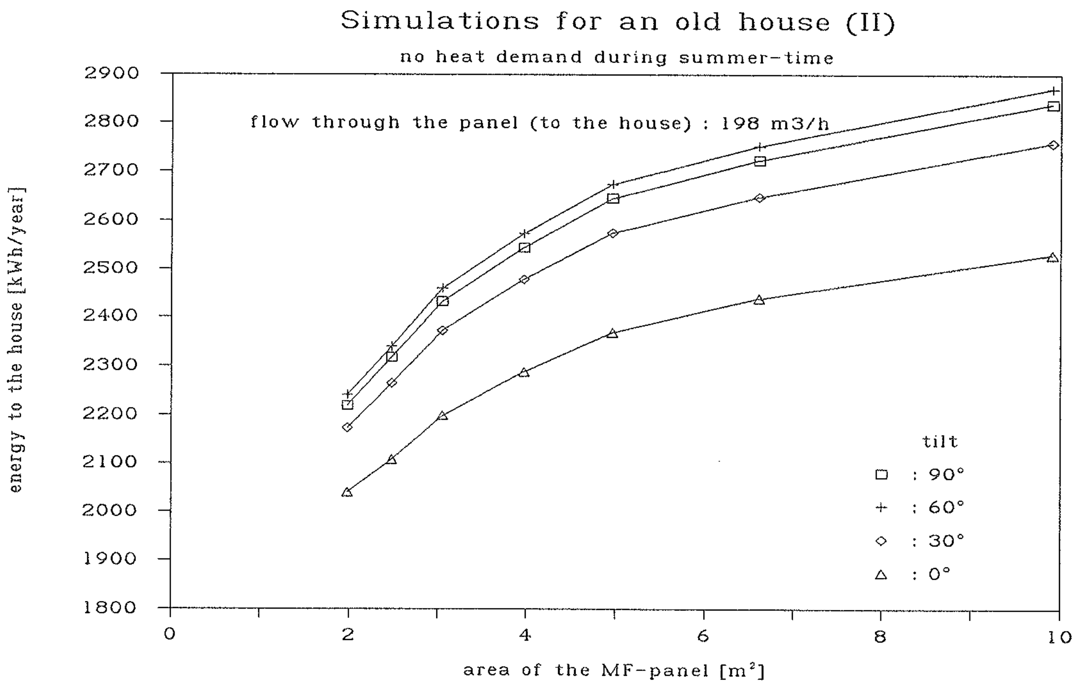

Figure 6.9 The annual performance of the MF-panel installed in an old house with no heat demand during summer-time - optimistic assumptions.

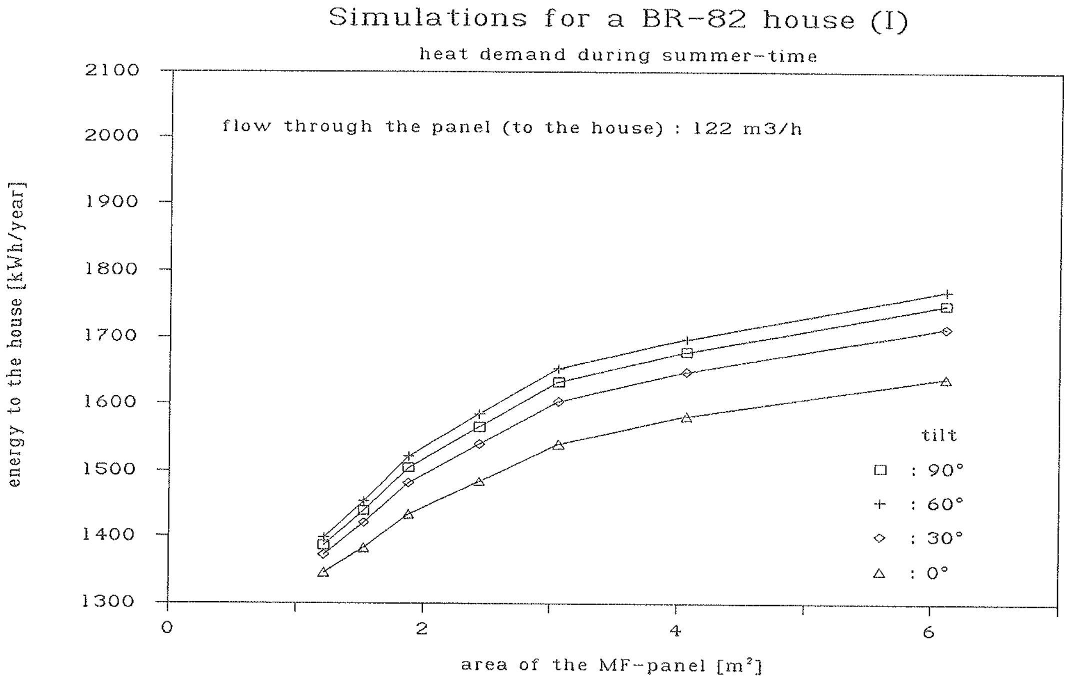

Figure 6.10 The annual performance of the MF-panel installed in a BR-82 house with heat demand during summer-time - pessimistic assumptions.

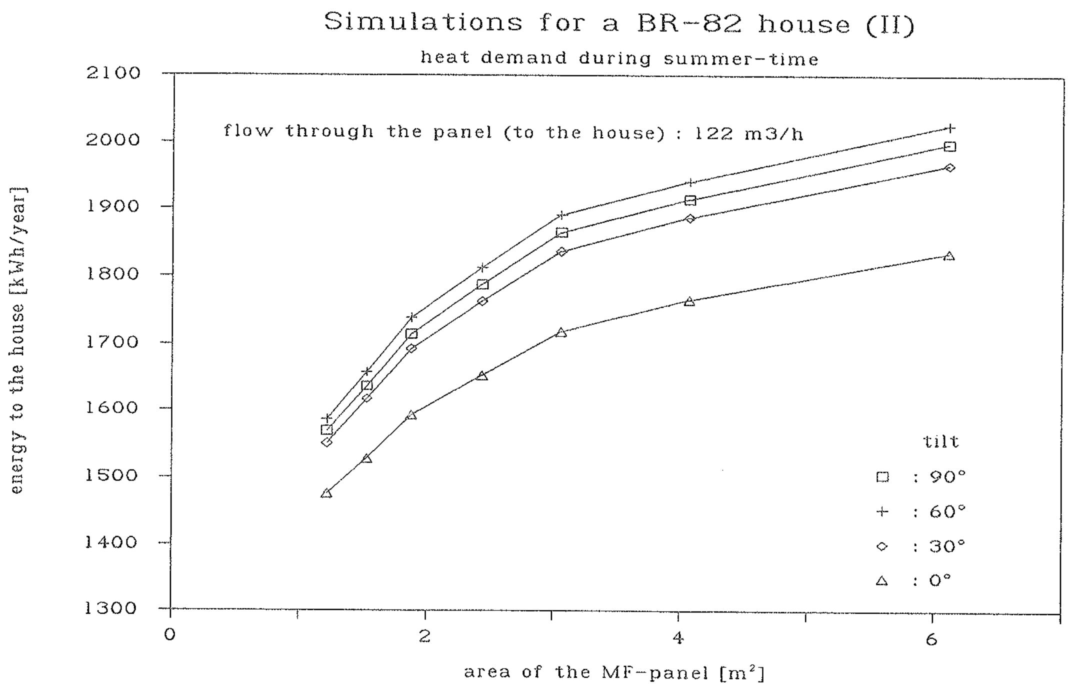

Figure 6.11 The annual performance of the MF-panel installed in a BR-82 house with heat demand during summer-time - optimistic assumptions.

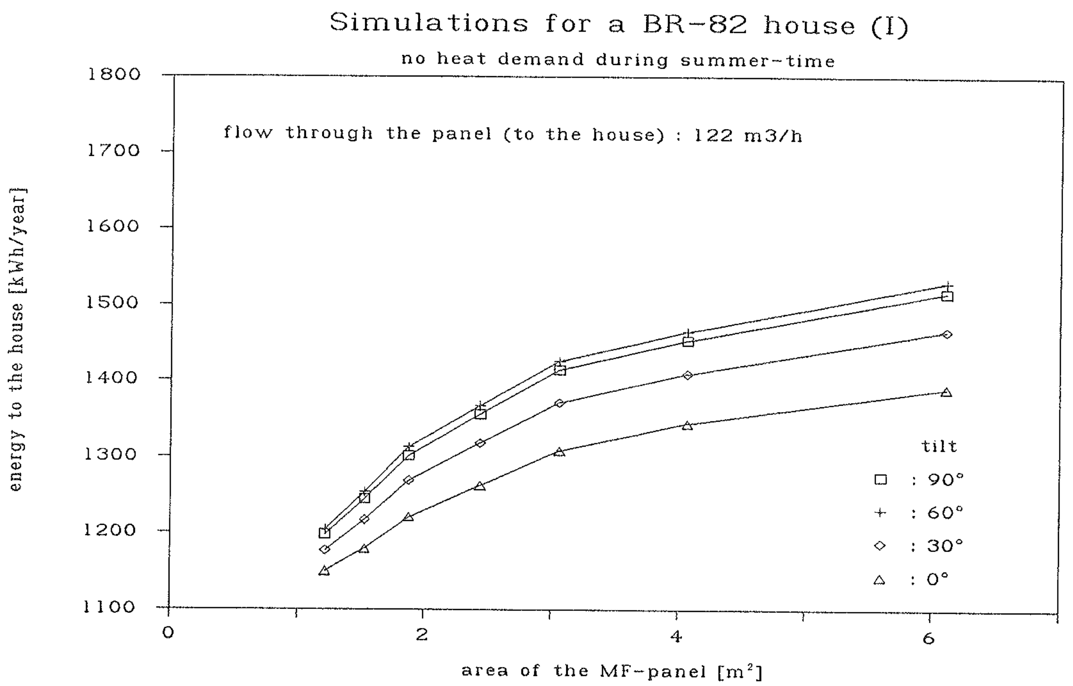

Figure 6.12 The annual performance of the MF-panel installed in a BR-82 house with no heat demand during summer-time - pessimistic assumptions.

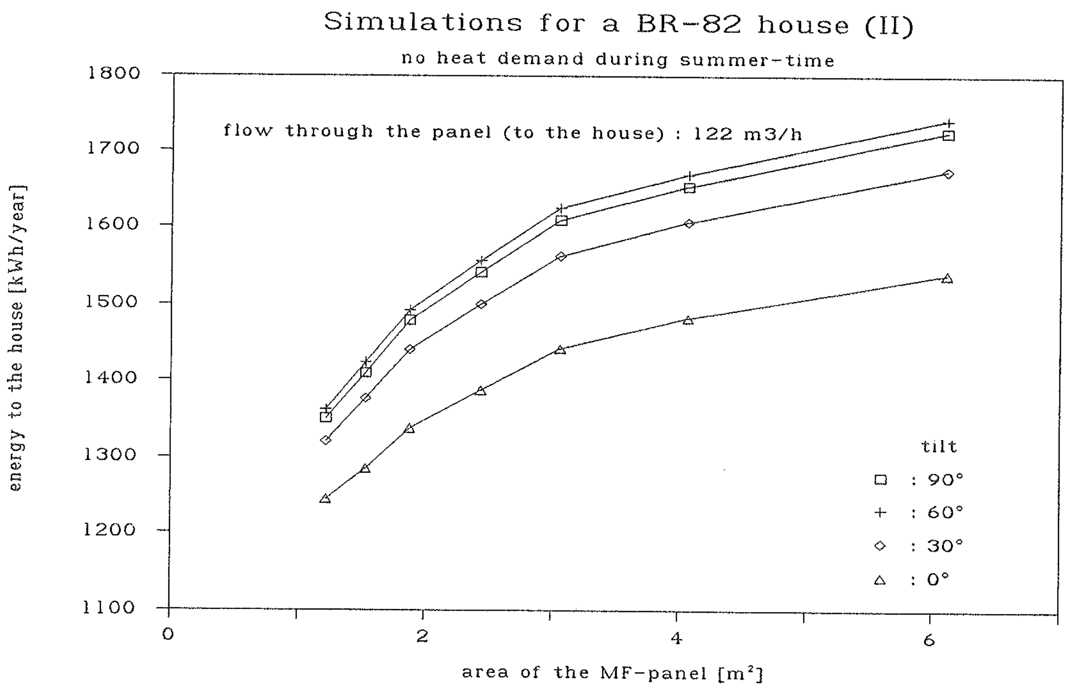

Figure 6.13 The annual performance of the MF-panel installed in a BR-82 house with no heat demand during summer-time - optimistic assumptions.

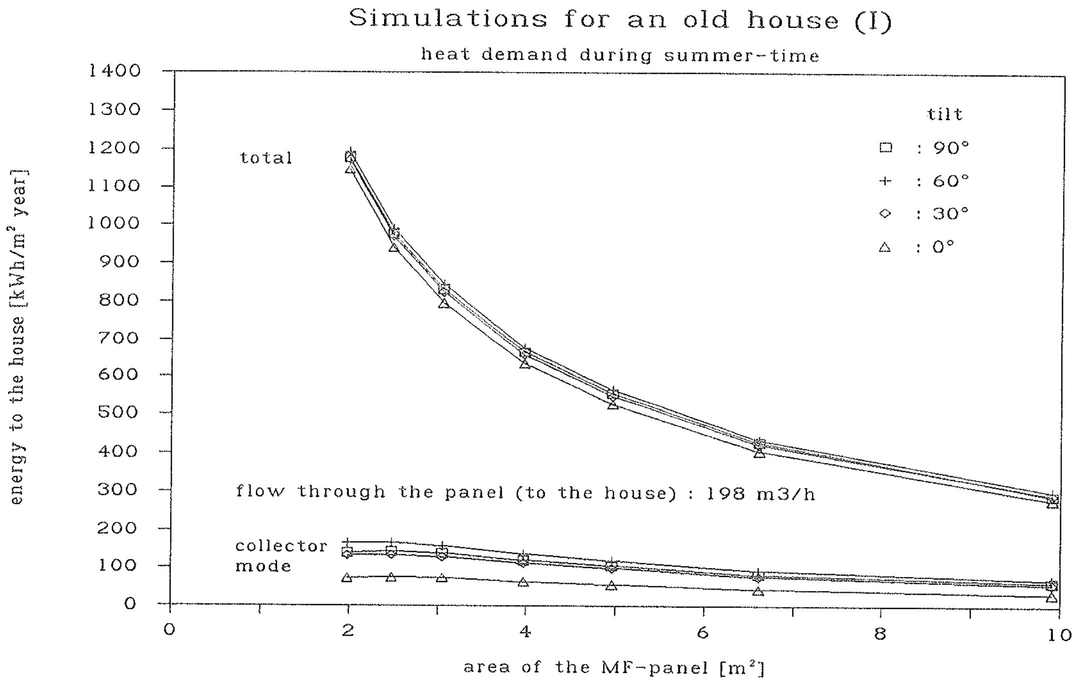

Figure 6.14 The annual performance per m2 of the MF-panel installed in an old house with heat demand during summer-time - pessimistic assumptions.

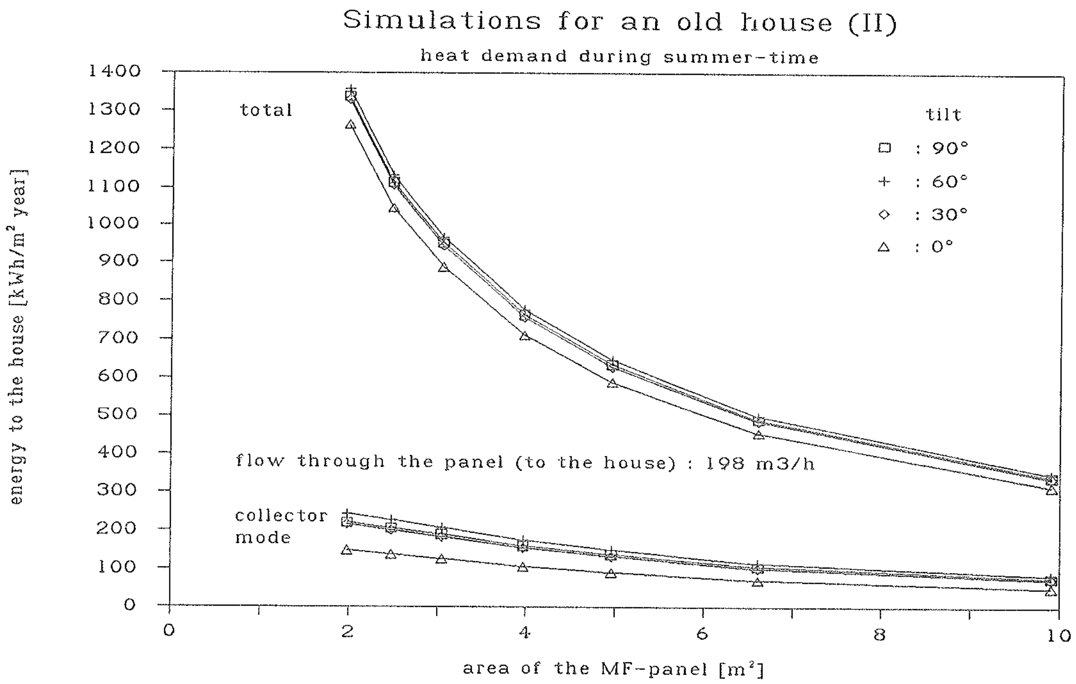

Figure 6.15 The annual performance per m2 of the MF-panel installed in an old house with heat demand during summer-time - optimistic assumptions.

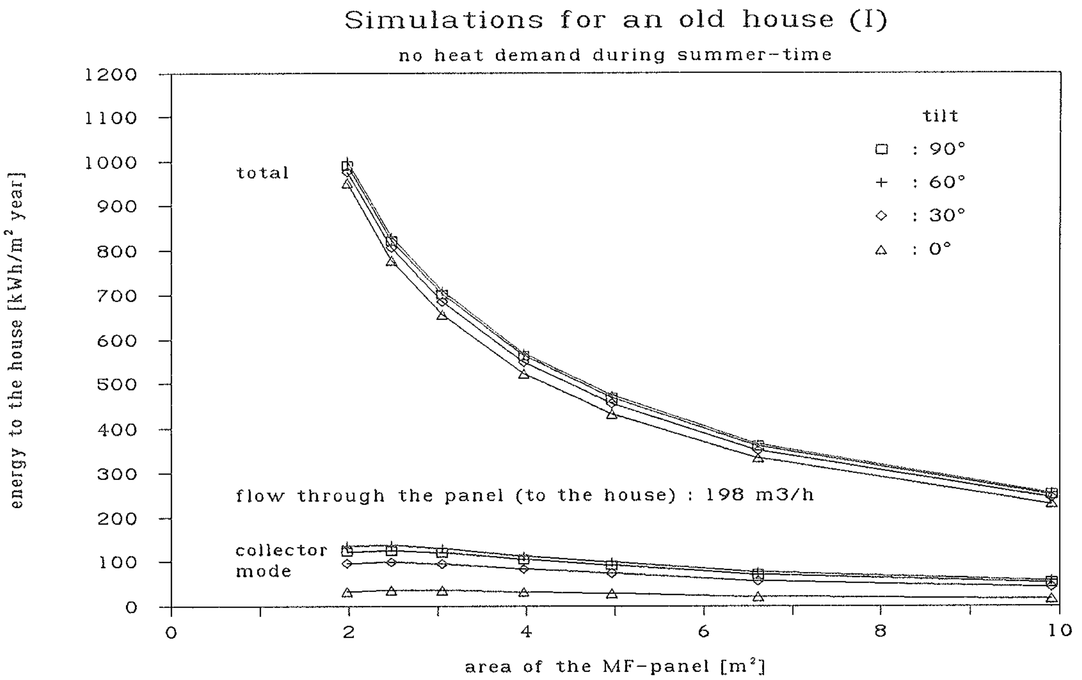

Figure 6.16 The annual performance per m2 of the MF-panel installed in an old house with no heat demand during summer-time - pessimistic assumptions.

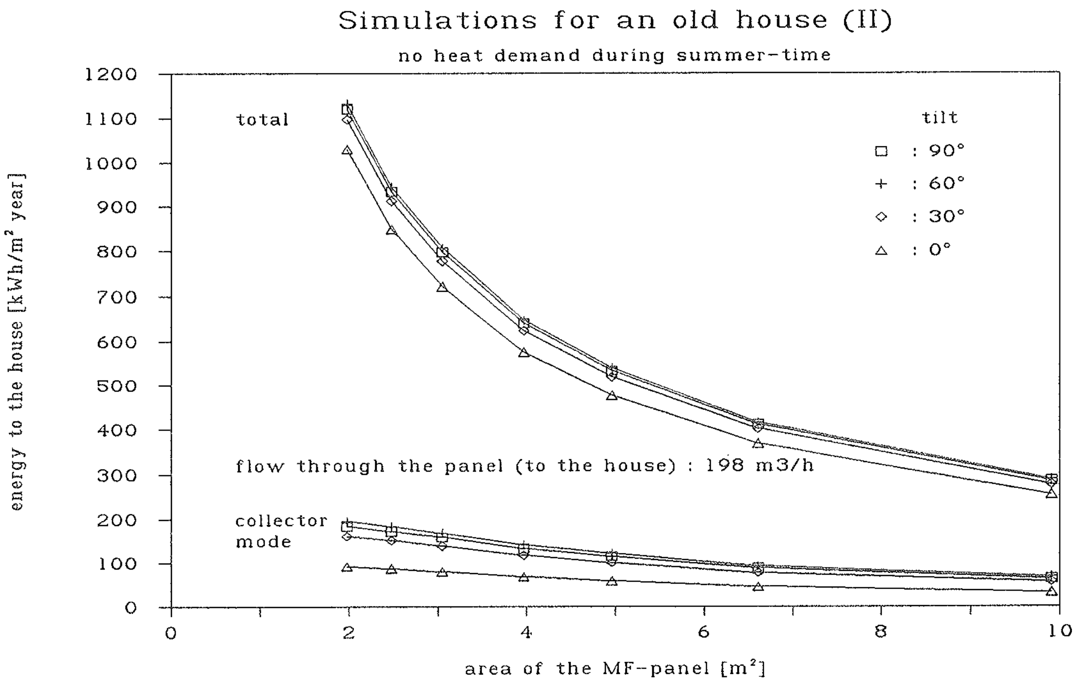

Figure 6.17 The annual performance per m2 of the MF-panel installed in an old house with no heat demand during summer-time - optimistic assumptions.

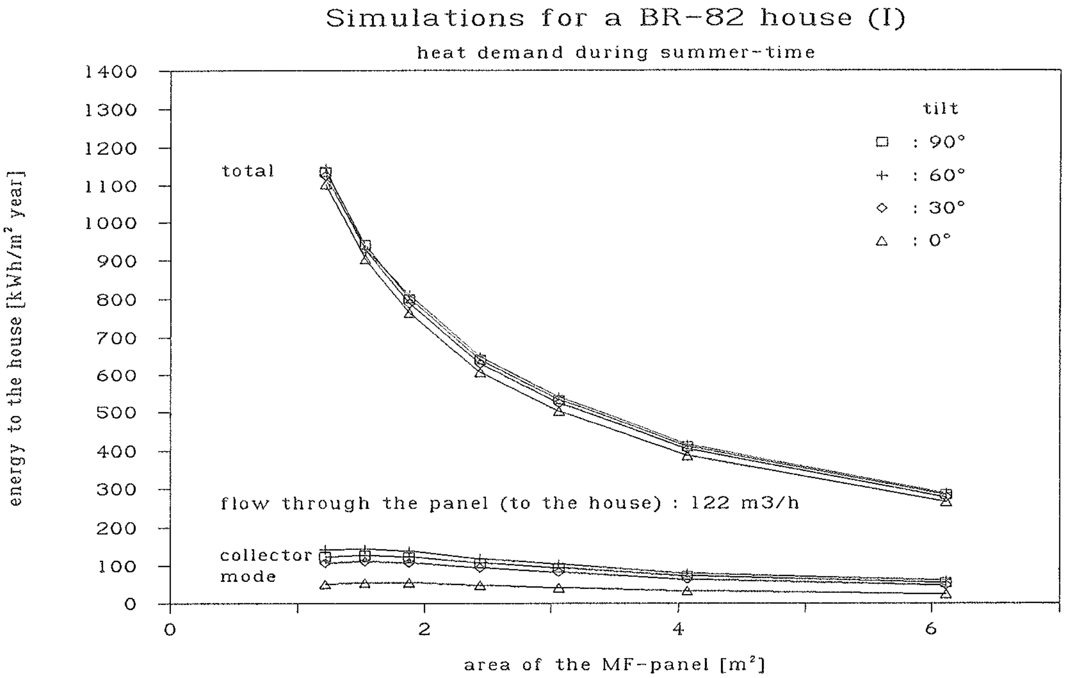

Figure 6.18 The annual performance per m2 of the MF-panel installed in a BR-82 house with heat demand during summer-time - pessimistic assumptions.

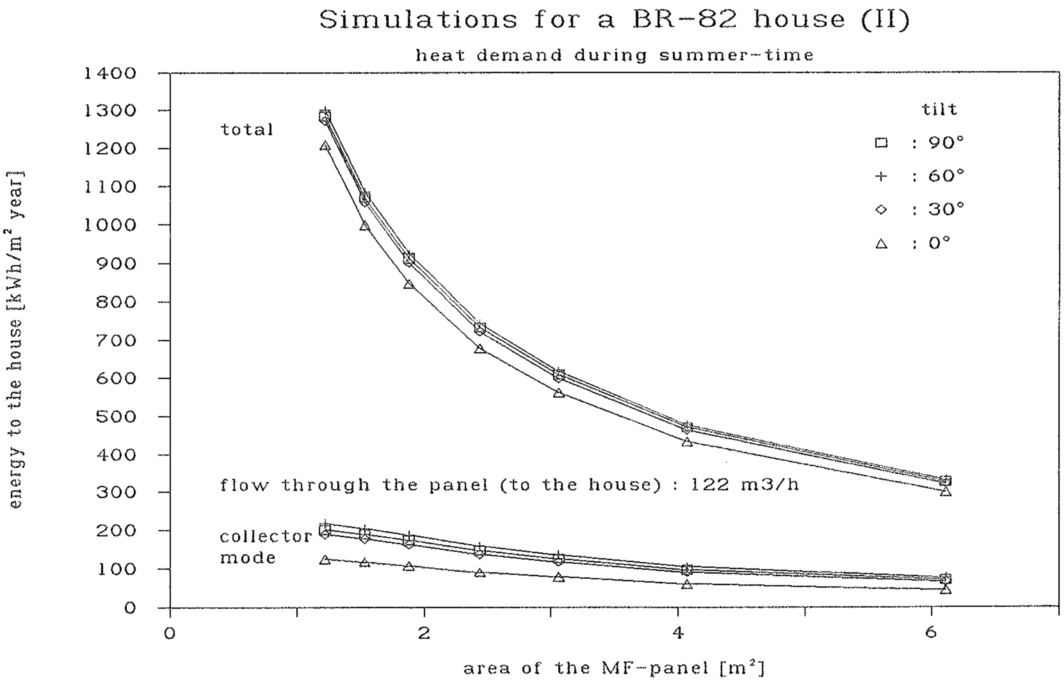

Figure 6.19 The annual performance per m2 of the MF-panel installed in a BR-82 house with heat demand during summer-time - optimistic assumptions.

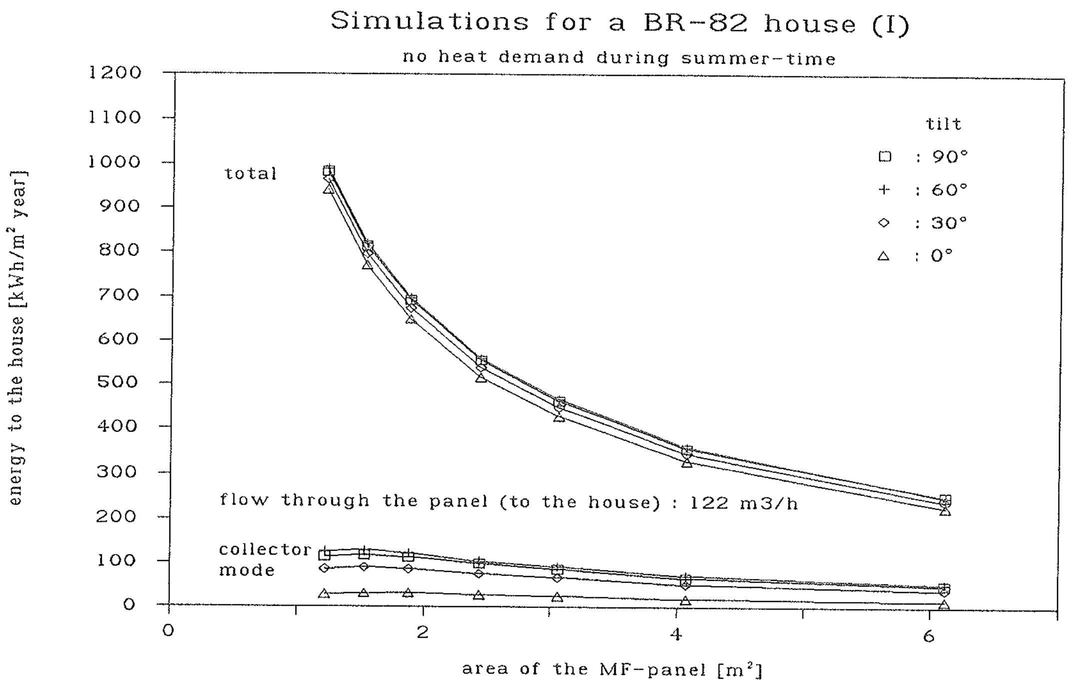

Figure 6.20 The annual performance per m2 of the MF-panel installed in a BR-82 house with no heat demand during summer-time - pessimistic assumptions.

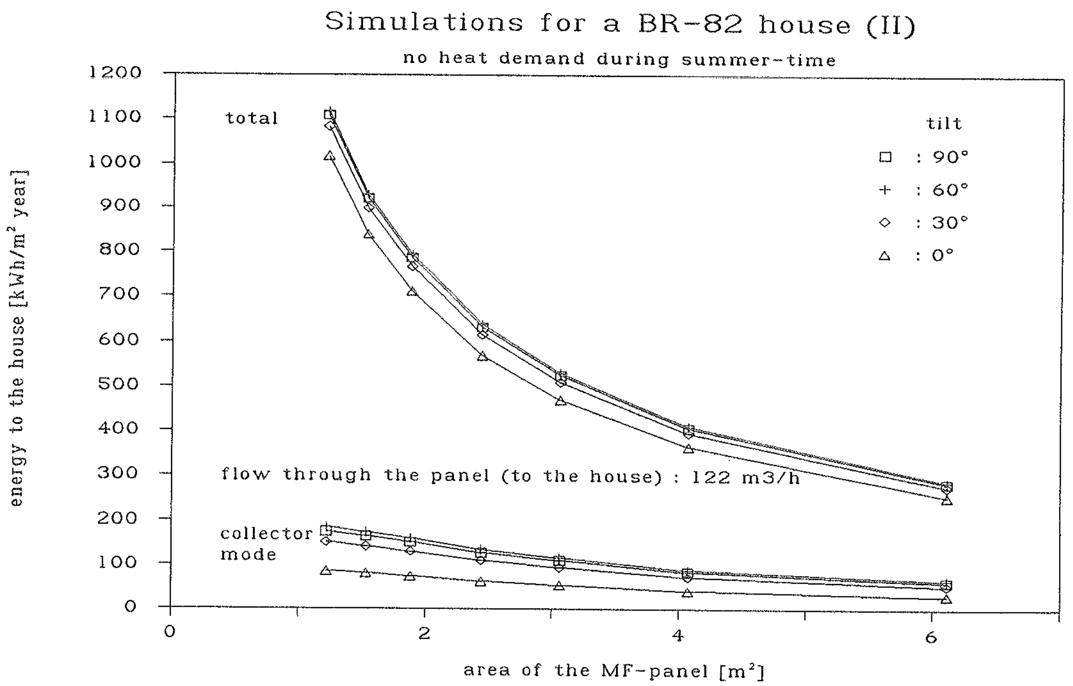

Figure 6.21 The annual performance per m2 of the MF-panel installed in a BR-82 house with no heat demand during summer-time - optimistic assumptions.

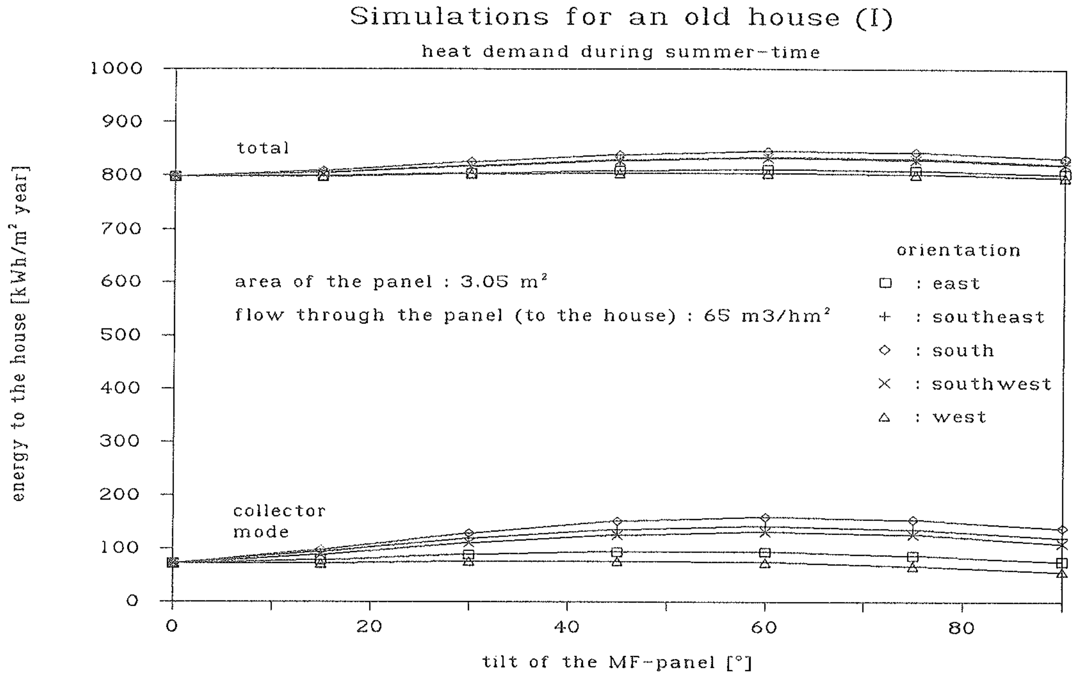

Figure 6.22 The annual performance per m2 of the MF-panel with a flow rate of 65 m3/m2h installed in an old house with heat demand during summer-time - pessimistic assumptions.

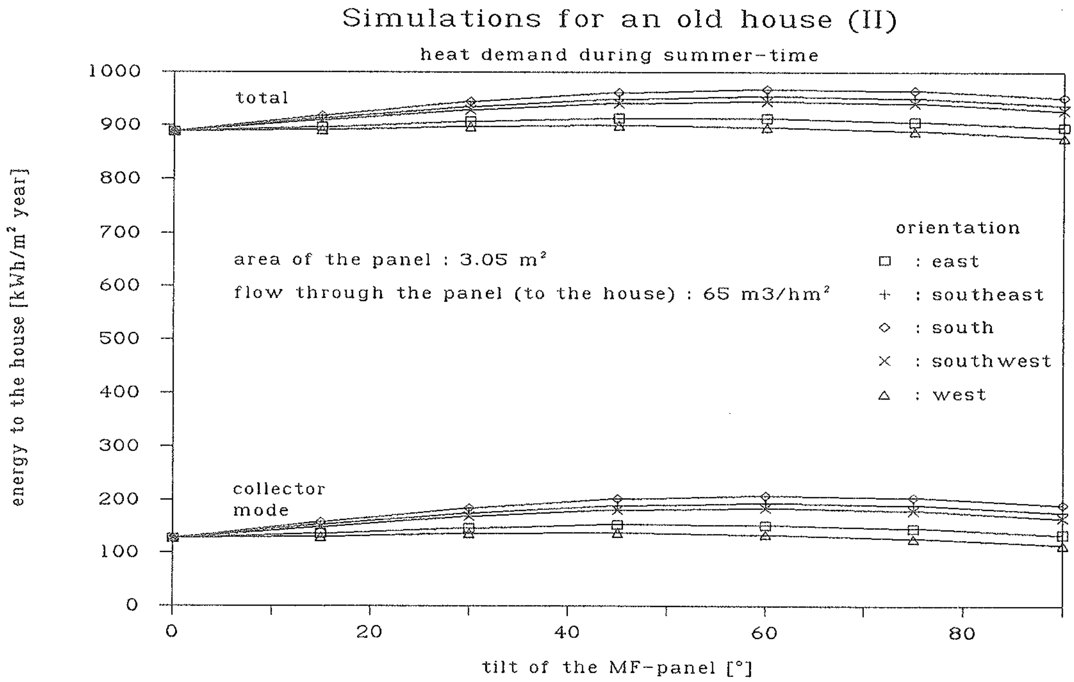

Figure 6.23 The annual performance per m2 of the MF-panel with a flow rate of 65 m3/m2h installed in an old house with heat demand during summer-time - optimistic assumptions.

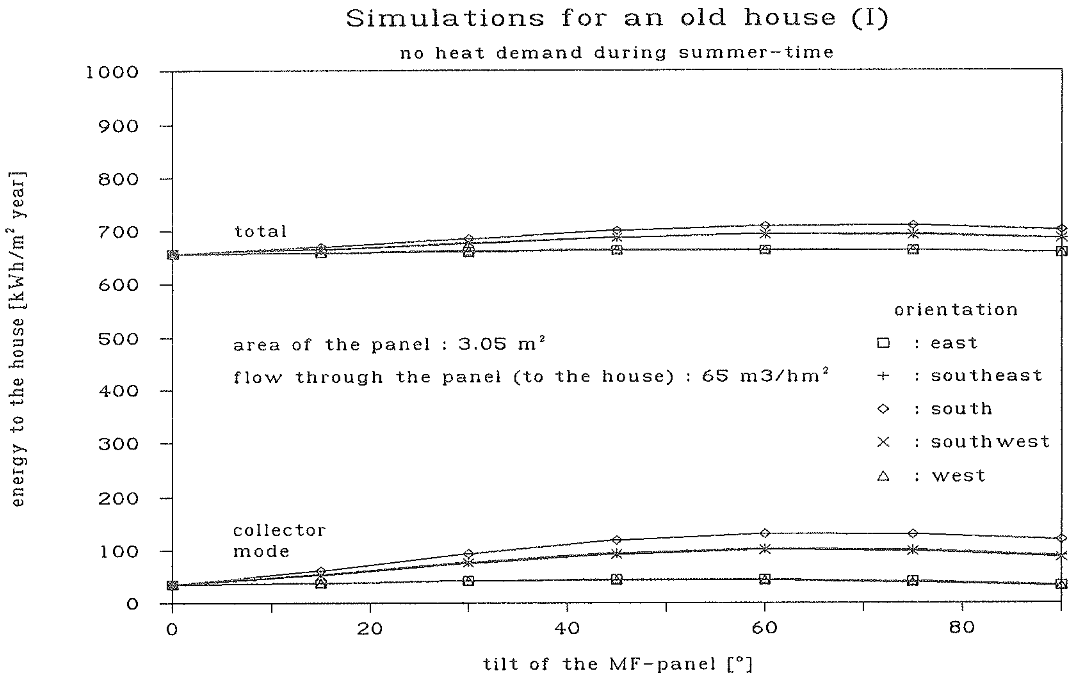

Figure 6.24 The annual performance per m2 of the MF-panel with a flow rate of 65 m3/m2h installed in an old house with no heat demand during summer-time - pessimistic assumptions.

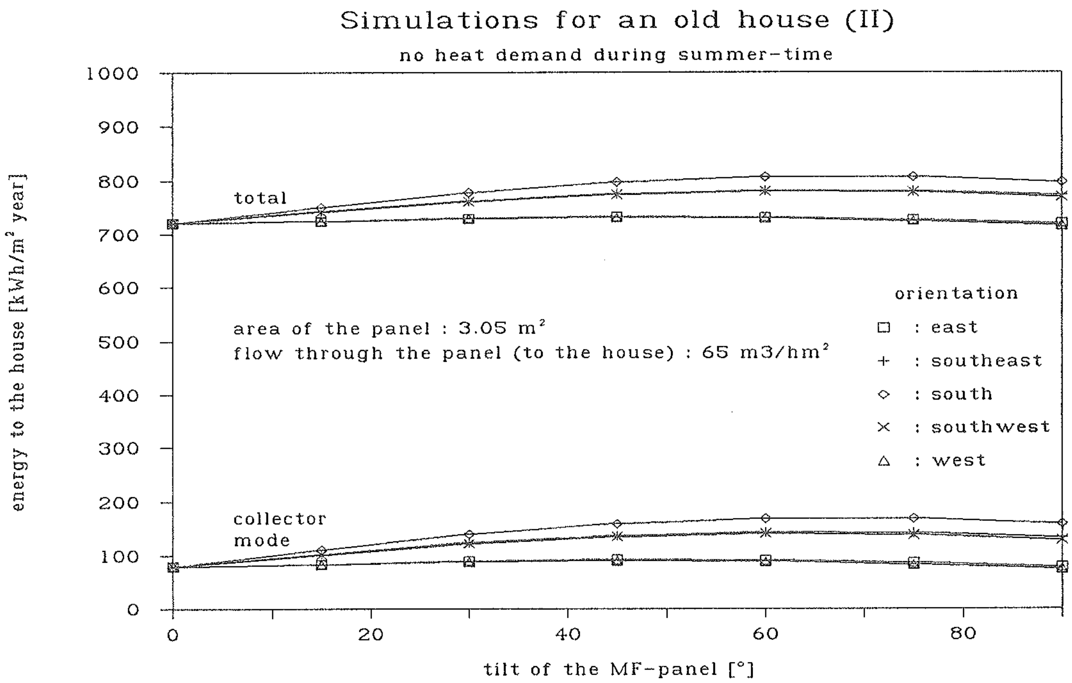

Figure 6.25 The annual performance per m2 of the MF-panel with a flow rate of 65 m3/m2h installed in an old house with no heat demand during summer-time - pessimistic assumptions.

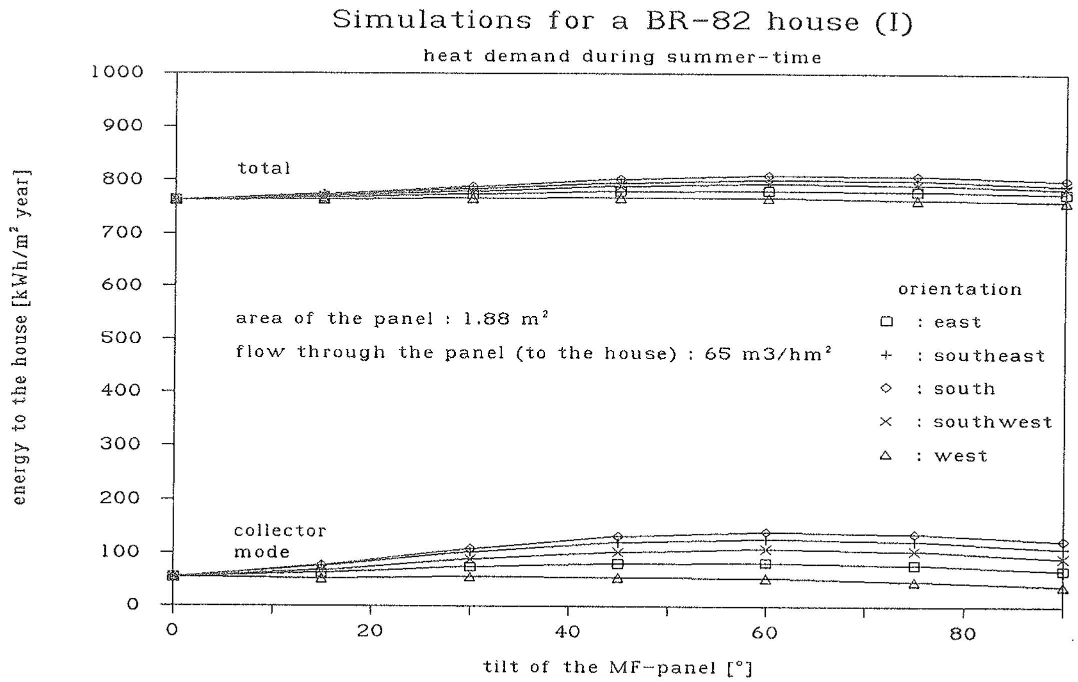

Figure 6.26 The annual performance per m2 of the MF-panel with a flow rate of 65 m3/m2h installed in a BR-82 house with heat demand during summer-time - pessimistic assumptions.

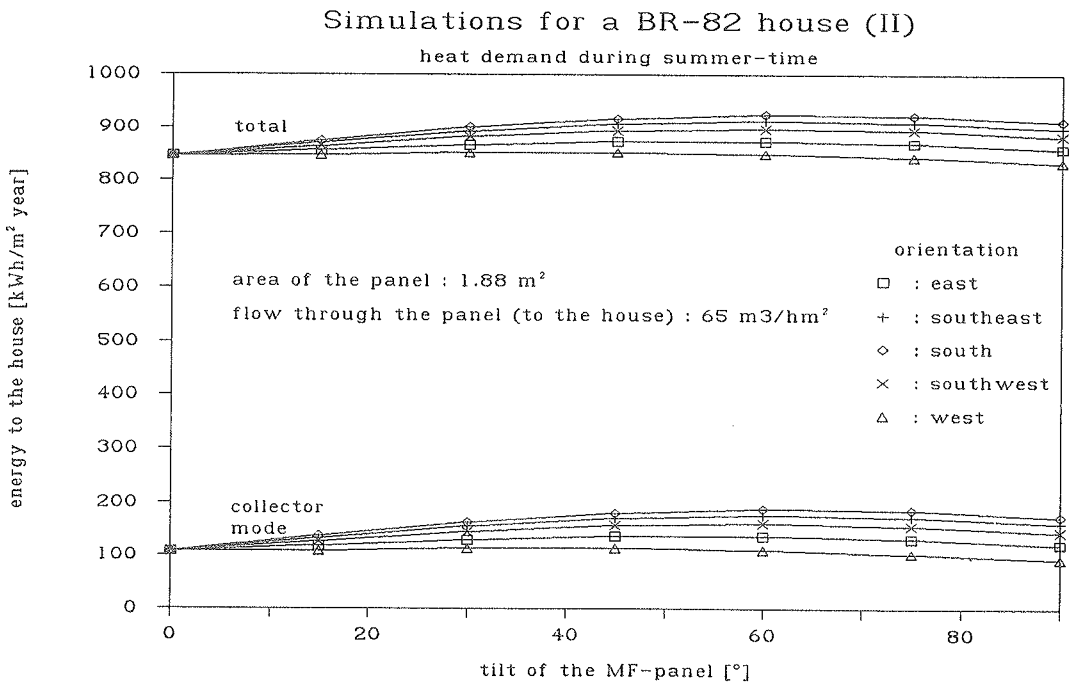

Figure 6.27 The annual performance per m2 of the MF-panel with a flow rate of 65 m3/m2h installed in a BR-82 house with heat demand during summer-time - optimistic assumptions.

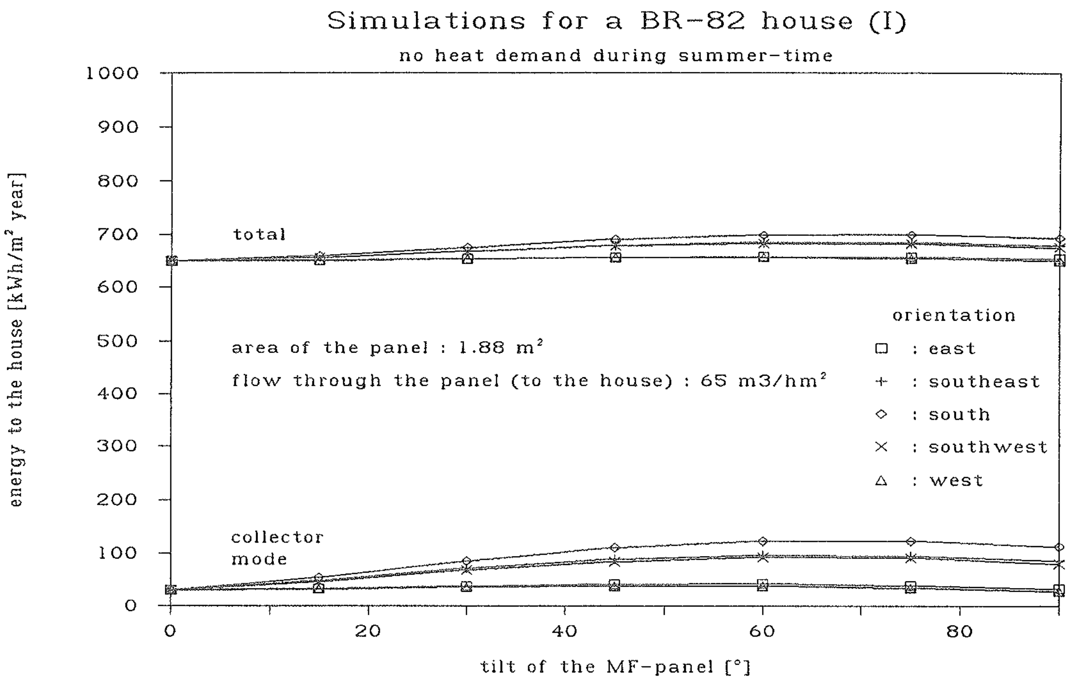

Figure 6.28 The annual performance per m2 of the MF-panel with a flow rate of 65 m3/m2h installed in a BR-82 house with no heat demand during summer-time - pessimistic assumptions.

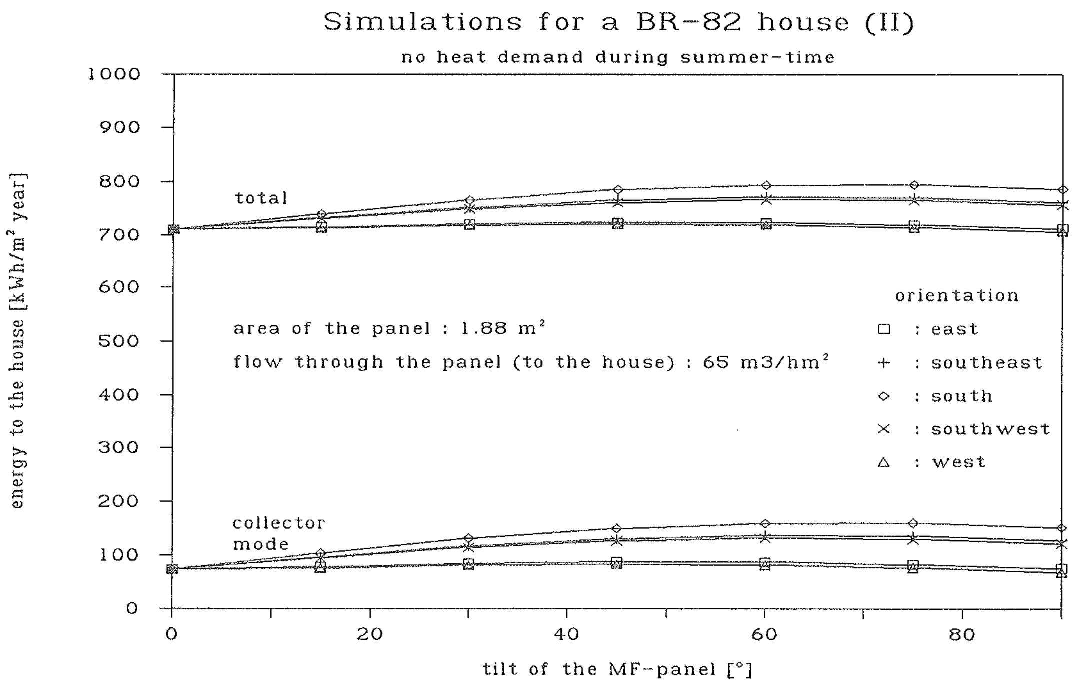

Figure 6.29 The annual performance per m2 of the MF-panel with a flow rate of 65 m3/m2h installed in a BR-82 house with no heat demand during summer-time - optimistic assumptions.

The figures show that there is a difference between the pessimistic and the optimistic way to simulate the performance of the MF-panel of between 8 and 14%. Investigations of the interaction between the solar collector and the heat exchanger should, therefore, be performed.

The purpose of the MF-panel is to pre-heat the incoming fresh air from the ventilation system. The MF-panel is, therefore, restricted only to try to cover a minor part of the overall heat demand of the house. Depending on the area of the panel, the orientation, the tilt and if there is a heat demand during summer-time, the MF-panel can cover between 9 and 15% of the overall heat demand, but 23-44% of the heat loss from the house due to ventilation. These fractions will be a bit larger if we consider for the reduced heat loss through the panel, if condensation occurs in the panel and if the panel was longer.

7 Economy

In the previous chapter the performance of a MF-panel mounted on a house has been calculated for different situations. In the present chapter the economy when installing a MF-panel is discussed.

The previous chapter has shown that the energy gain will be found between 225 and 1350 kWh/m^2 - highest for high flow rates (small collector area), a tilt of 60° and south facing orientation, while the lowest performance will be found for small flow rates (large collector area) and a tilt of 0°. For a medium flow rate of 65 m^3/m^{2}h, a tilt of 60° and a south facing orientation the energy gain will be between 700 and 970 kWh/m^2 (without energy gain from the sun the output will be between 640 and 770 kWh/m^2). If we compare this performance with the performance of a traditional water based solar heating system for space heating, which has an annual performance of 250-300 kWh/m^2 it is seen, that the MF-panel performs about three times better than the traditional solar heating system. This is of course due to the fact that the MF-panel will also gain energy from the exhaust air from the house. It is, therefore, not really fair to compare the MF-panel to a traditional solar heating system.

A heating system with a MF-panel is rather simple: There is not, as for the traditional solar heating system, a need for a storage, the control of the system is also simple, and the MF-panel is rather inexpensive as most of it is already 'paid for' by the wall or roof (the insulation and the trapezium corrugated metal sheet). There has not been time for making any calculations of the price of MF-panels (this will be made in a demonstration project - see the next chapter), but it can be said that a heating system with a MF-panel will be cheaper than a traditional solar heating system, and that the economy will, therefore, be better than for a traditional solar energy system even if the heating system with the MF-panel will use quite some electrical power for running the ventilators. The electrical demand for the ventilators in a traditional ventilation system with heat recovery can be 10-15% of the energy gained from the heat exchanger in the system. In a liquid based solar heating system the energy consumption of the circulation pump in the collector loop lies below 5%.

As already mentioned, it is not fair to compare the MF-panel to a traditional solar heating system. In real buildings the MF-panel will substitute the heat recovery unit (heat exchanger) in the ventilation system.

The performance of a ventilation system with a cross-flow heat exchanger has been simulated for similar conditions as the MF-panel was exposed to. In the following example the flow through the MF-panel has been chosen to be 65 m^3/m^{2}h, the tilt is 60° and the orientation is south. Two different situations have further been chosen to show the range of the results:

1) Energy demand: Old house with heat demand during summer-time.
   Simulation: Optimistic,

2) Heat demand: BR-82 house with no heat demand during summer-time.
   Simulation: Pessimistic.

The simulated results discussed in the previous chapter have been used. This means that the reduced heat loss through the panel has not been considered. Neither has a possible increase of the efficiency, if the panel was longer, been considered. It is further assumed that no condensation takes place in the panel or the cross-flow heat exchanger.

The efficiency of the heat exchanger is assumed to be 65%.

Situation	Energy gain	
	MF-panel kWh/year	Cross-flow heat exchanger kWh/year
1	2952	4885
2	1312	2514

Table 7.1 The annual performance of the MF-panel and a cross-flow heat exchanger in a ventilation system.

From the table it is seen that the performance of the system with the MF-panel is 60 and 52% of the performance of the system with the cross-flow heat exchanger. This means, that the MF-panel must only cost half the price of a cross-flow heat exchanger, which does not sound unrealistic as the marginal cost of a MF-panel (compared to a wall or a roof) is expected to be low. This will be investigated further during the future demonstration project.

8 Demonstration project

On the basis of the results and experience presented in this report the group behind the project has applied to the European Communities for financial support to a demonstration project comprising a real heating system utilizing the MF-panel. The European Communities have approved to support the project. The projecting of the system is expected to start at the beginning of 1990, and the construction will take place by the end of 1990. After that, measurements will be performed on the system for two years.

The project contains the installation of about 200 m² MF-panels on the roof of one of the buildings of Wewers Teglværker a/s (a brickyard) in Helsinge, a town situated approximately 50 kilometres north of Copenhagen.

The MF-panels will be mounted on the roof of a workshop for manufacturing brick-beams as shown in figure 8.1.

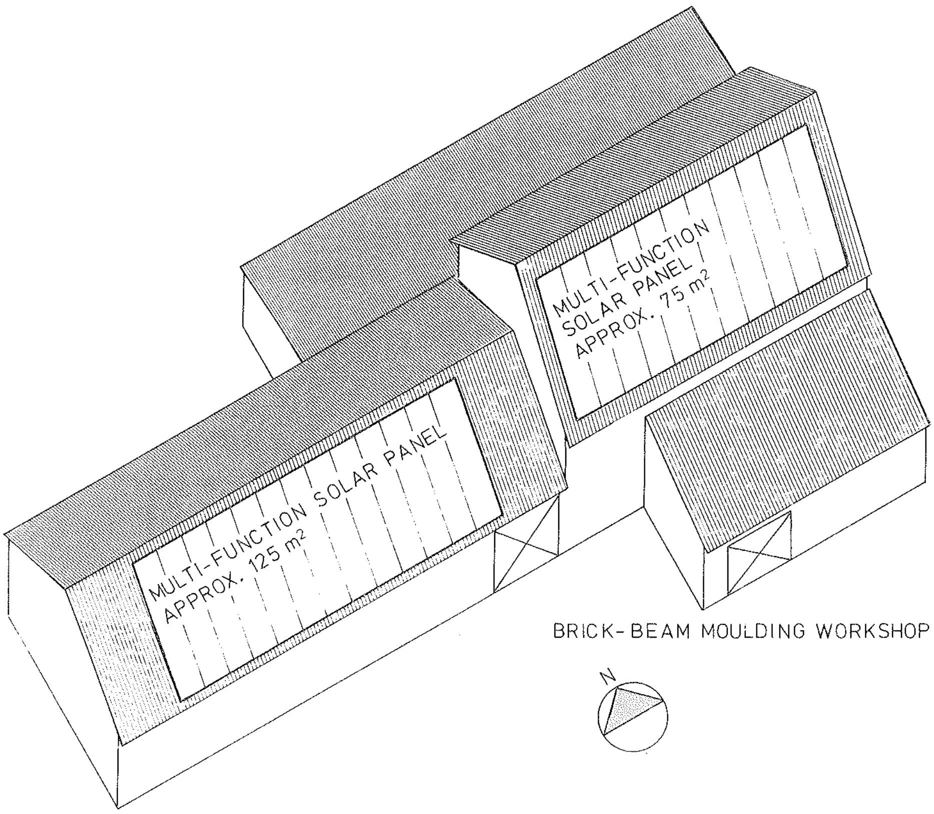

Figure 8.1 The workshop for manufacturing brick-beams with the MF-panels on the roof.

The aim of the demonstration project is to:

- substitute electrical power and natural gas for space heating purposes,
- raise the temperature of the water for the setting process,
- improve the working conditions.

The pre-heated air from the MF-panels is supplied to the existing heating system which consists of a gas fired boiler and water-to-air heat exchangers. The pre-heated air is expected to be delivered to the water to air heat exchangers (see figure 8.2). The pre-heated air is also, via an air to water heat exchanger, used to raise the temperature of the water for the setting process, in order to precipitate the solidification process. The relative humidity of air in the workshop is very high, the ventilation created by the MF-panel system will, therefore, improve the working conditions by lowering the relative humidity.

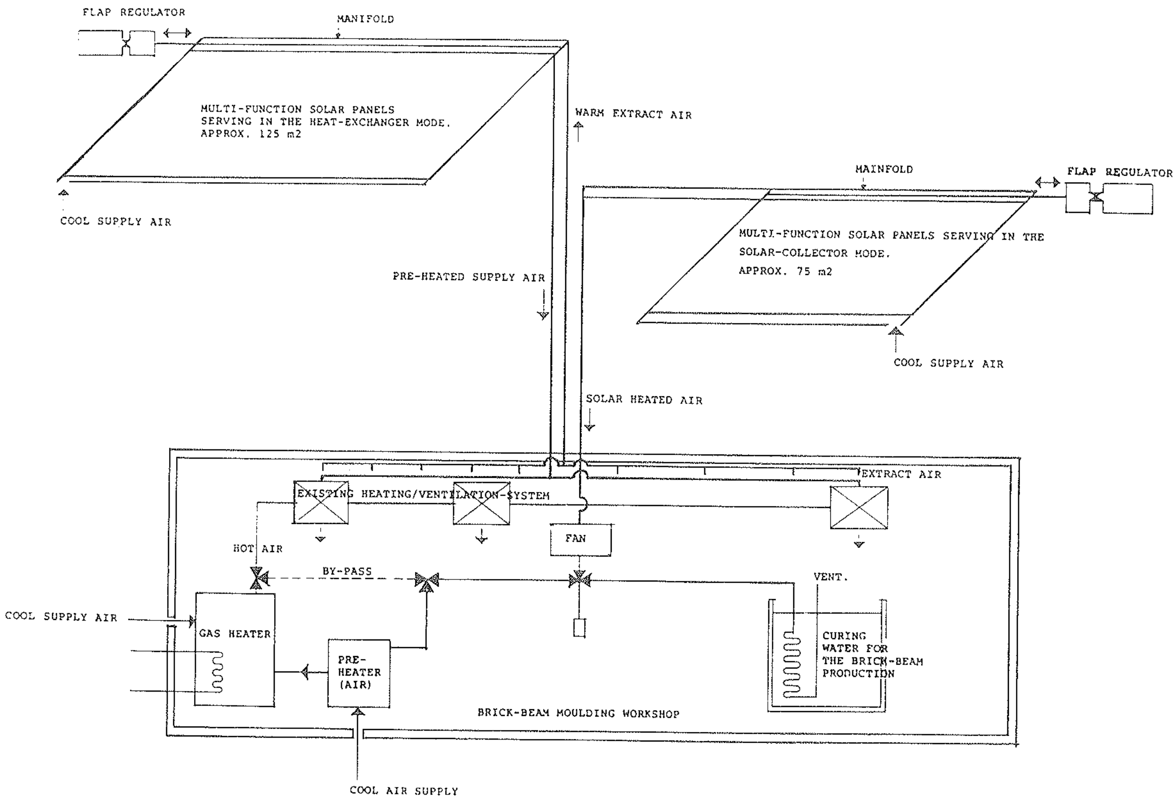

Figure 8.2 Outline of a suggestion for the heating/ventilation system of the demonstration project.

In the demonstration project it will be possible to investigate several of the interesting processes with which it has not been possible to go into details during the present project - eg the interaction between solar collector and heat exchanger and the influence of condensation as the exhaust air from the workshop is rather humid.

9 Conclusion

The MF-panel design is a rather new concept, it has, therefore, not been possible to establish knowledge of all the processes related to this design. The work has been concentrated on testing of two different prototypes of the MF-panel. Some thermal processes have, however, briefly been dealt with. Simulations have also been performed in order to show the possible range of the annual performance of a MF-panel installed in a house.

Two prototypes of MF-panels have been successfully tested during the project. The efficiency of the MF-panel working exclusively as solar collector and exclusively as a heat exchanger for preheating of fresh air has been determined as a function of the flow rate through the panel.

The highest efficiency, when working as a solar collector, is reached when having a transparent cover and letting the trapezium corrugated metal sheet work as absorber - 35% at a flow rate of 30 m^3/m^2h and 60% at a flow rate of 100 m^3/m^2h. This decreases further the influence of wind on the cover. The test was performed on the MF-panel having a transparent cover of a double-walled ribbed plate. This reduces the heat loss through the cover, but also reduces the transmittance of solar irradiation. If the transparent cover only consists of one layer, the heat loss through the cover will be larger, but the transmittance of solar irradiance will also be larger. It is not possible, from the work made during this project, to choose between these two covers, but as the simulations show, the overall performance of the MF-panel only depends a little on the performance of the MF-panel as solar collector. Therefore, there will only be a small difference if there are one or two transparent covers. In order to have a sufficient strength of the cover, the cover consisting of only one layer, has to be rather thick; it is, therefore, estimated that the price of the two covers will be almost identical.

If the cover is opaque the efficiency is considerably lower than if the cover is transparent, and the efficiency depends very much on wind along the surface of the cover. This cover, however, is cheaper than the transparent cover. The choice of type of cover can, therefore, only be based on an optimization of not only the MF-panel but of the whole ventilation system.

The efficiency of the proto-types working purely as heat exchangers was measured to be about 30%. This efficiency is not dependent of the type of cover. The efficiency may be decreased if the MF-panel is not mounted vertically, due to a higher heat loss through the cover - this decrease will be greatest for a MF-panel with only one layer in the cover. It has been shown that the efficiency can be increased considerably if condensation occurs in the panel. It is not likely that condensation will occur in MF-panels installed in residential buildings, because no condensation will take place before the relative humidity of the air exceeds 60% (at 20°C). The MF-panel will decrease the heat loss through the wall (or the roof) compared to a normal wall (or roof) because the warm exhaust air is led down the outside of the insulated wall. Two examples show that the net heat loss through the wall can be reduced to 11% during periods without solar radiation on the wall. The annual effect of this reduction has, however, not been calculated as it demands rather complicated simulations.

A first attempt has been made in order to establish a theory for the performance of the MF-panel as a solar collector and as a heat exchanger. This is, however, a non trivial task and the preliminary result shows rather poor agreement with the measurements. The predicted efficiency of the solar collector is far too high, while the predicted performance of the heat exchanger is far to low except for small flow rates where the theory agrees very well with the measurements. Even if the theory does not agree with the measurements, the theory has been used to predict the changes of performance if the dimensions of the MF-panel were changed. This was made even if the theory and the measurements will give different absolute results, the trend could very well be the same. If the length of the MF-panel is increased to double length and the other parameters are identical, the theory shows that the efficiency of the solar collector will be increased by 1.5-8% (highest for low flow rates), while the efficiency of the heat exchanger will be increased by 18%. This shows, that by optimization it will most probably be possible to increase the performance of the MF-panel. This demands, however, a model (theory) describing the panel. Efforts should, therefore, be made to develop such a model, as the output of the research work will be better performing MF-panels, and thereby increase the use of this type of energy saving component.

Several simulations have been performed to establish a sort of guide line for future design of systems containing MF-panels. The results from these simulations are shown graphically making them rather easy to use. The simulations show that the energy gain from the sun only gives a small contribution to the overall performance of the MF-panel - 3-25% of the overall performance depending of area, tilt and orientation of the panel and the heat demand of the house. This means that it is not that important to optimize the MF-panel as solar collector.

The simulations show that 9-14% of the total heat demand for the chosen houses can be covered by the MF-panel. The MF-panel can cover 23-44% of the heat loss due to ventilation.

The annual energy gain from a MF-panel is calculated to be between 225 and 1350 kWh/m^2 depending on the size of the MF-panel. Compared to a traditional solar heating system for combined space heating and hot water production, which has an annual performance of 250-300 kWh/m^2, it is seen, that the MF-panel may have a performance up to four times higher than a traditional solar heating system which, of course, is due to the fact that the MF-panel will also gain energy from the exhaust air from the building. Ventilation systems with MF-panels further have the benefit that they do not need any storage and the control is rather simple - these systems are, therefore, cheaper than traditional solar heating systems. The ventilation systems described in this report covers, however, a smaller fraction of the heat demand of the here simulated houses than the traditionally designed solar heating system for combined space heating and hot water production - 9-14% versus about 25%. The fraction of covered energy demand can be increased by combining the MF-panel system with a traditional solar heating system for domestic hot water supply (the fraction of covered heat demand will then be increased to 19%) and by lowering the heat loss due to transmission, say, by installing it in low energy houses where the heat loss due to ventilation is about half the total heat demand.

Compared to a common cross-flow heat exchanger the price of the MF-panel has to be half the price of the cross-flow heat exchanger in order to be competitive. This should be possible to obtain as the marginal cost when changing a normal wall (or roof) to a MF-panel is low, because the only parts missing are the cover and the manifolds.

Many of the areas which have not been dealt with or only briefly been dealt with in this project will be investigated in a future demonstration project.

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