MF-demonstration project at Wewer's Brickyard in Helsinge

by
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Measuring system:	The Thermal Insulation Laboratory

Sponsor:

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Preface

The present report describes the experience gained from measurements carried out on a building equipped with a 126 m^2 Multi-Function Solar Energy Panel. The report is the conclusion of a project co-financed by the Commission of the European Communities with the name "Demonstration of Multi-Function Solar Energy Panels", SE 417/87. Part of the measuring system has been supported by a project financed by the Danish Ministry of Energy J.no. 51181/91-0020.

The work within the project has been carried out in co-operation between the Thermal Insulation Laboratory, Technical University of Denmark, the Architects Arne Meldgaard & Co, and Techline Energy Systems.

The demonstration project has earlier been described in a status report (Jensen, 1992) and an article to the Danish magazine "Byggeindustrien" ["The Building Industry"], (Jensen, 1993).

Table of Contents

1. Introduction

The present report describes the experience gained from the project "Demonstration of Multi-Function Solar Energy Panel". The project was realised at Wewer's Brickyard in Helsinge, in the northern part of Zealand, Denmark - see figure 1.1.

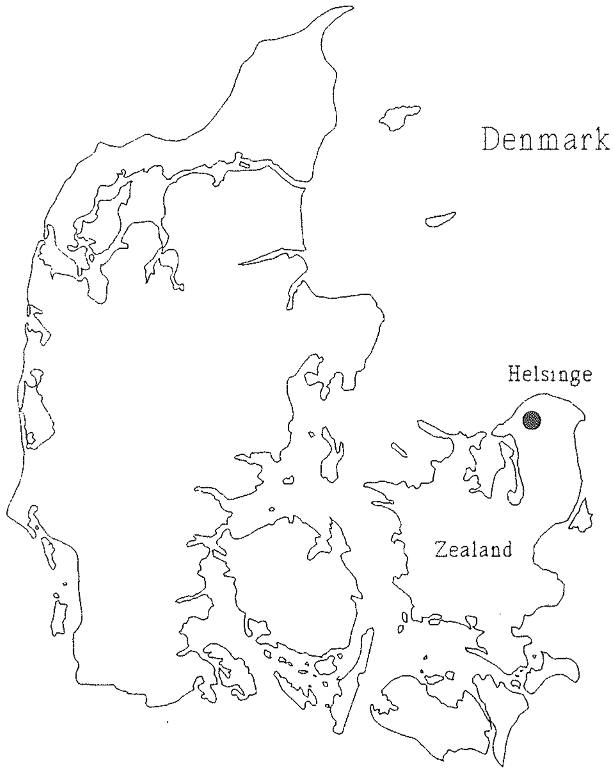

Figure 1.1. The location of the demonstration project.

The Multi-Function Solar Energy panel - in the following abbreviated to MF-panel - was developed in a previous R&D project financed by the Danish Ministry of Energy (Jensen, 1990a). The concept of the MF-panel is shown in figure 1.2. The outer part of the panel consists of a flat plate - either a metal sheet or a transparent plate - behind this plate is located a metal sheet with a trapezium corrugated profile. The two plates are mounted in front of a normally insulated outer wall. At the top of the panel there are box-shaped manifolds - see figure 1.2. In this way it is possible to let air into the two sets of air gaps formed by the trapezium corrugated metal sheet. The panel can, therefore, act both as a solar collector and as a heat exchanger between fresh air to the building and exhaust air from the building. 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 1.3 shows the results from tests on a prototype of the MF-panel working as a solar collector (both with a metal sheet and a transparent double walled plastic sheet as cover), while figure 1.4 shows the results from tests of the MF-panel as a heat exchanger (also with the two different covers) - (Jensen, 1990a).

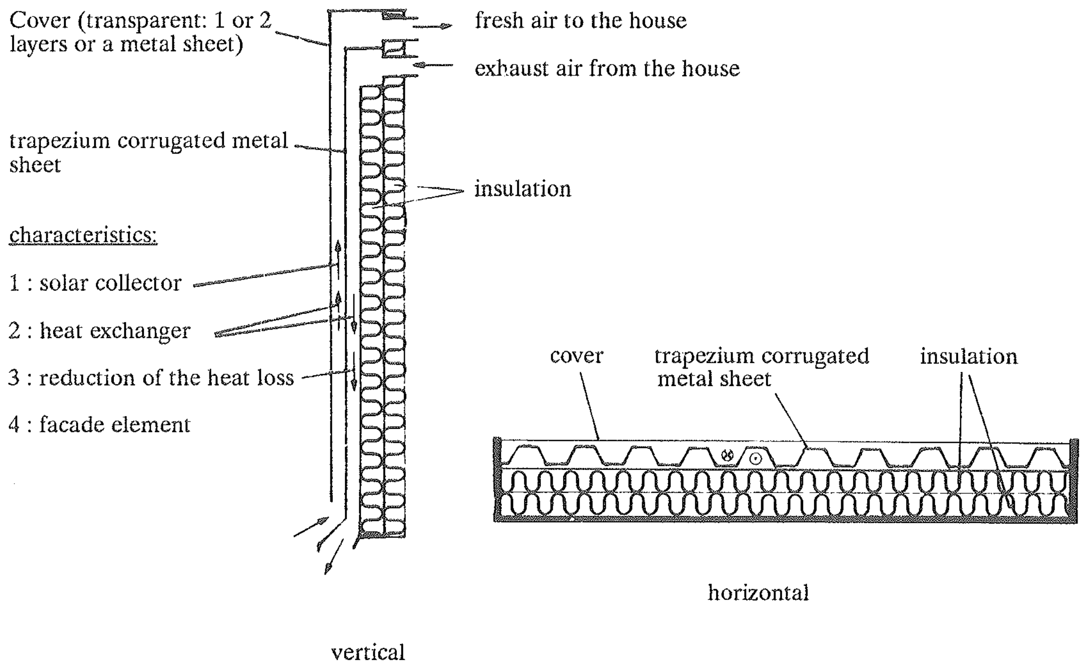

Figure 1.2. Schematic sections through the Multi-Function solar energy panel (MF-panel).

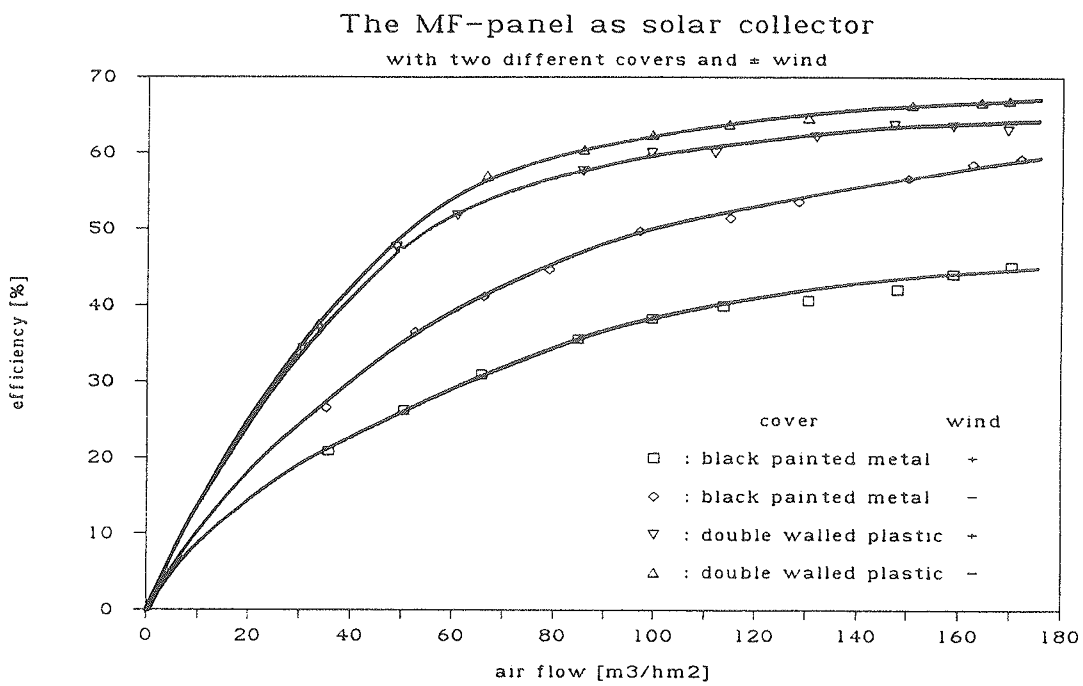

Figure 1.3. The results from tests on the MF-panel working as a solar collector for pre-heating of fresh air. The efficiency has been measured with and without a simulated influence of wind of approximately 2 m/s.

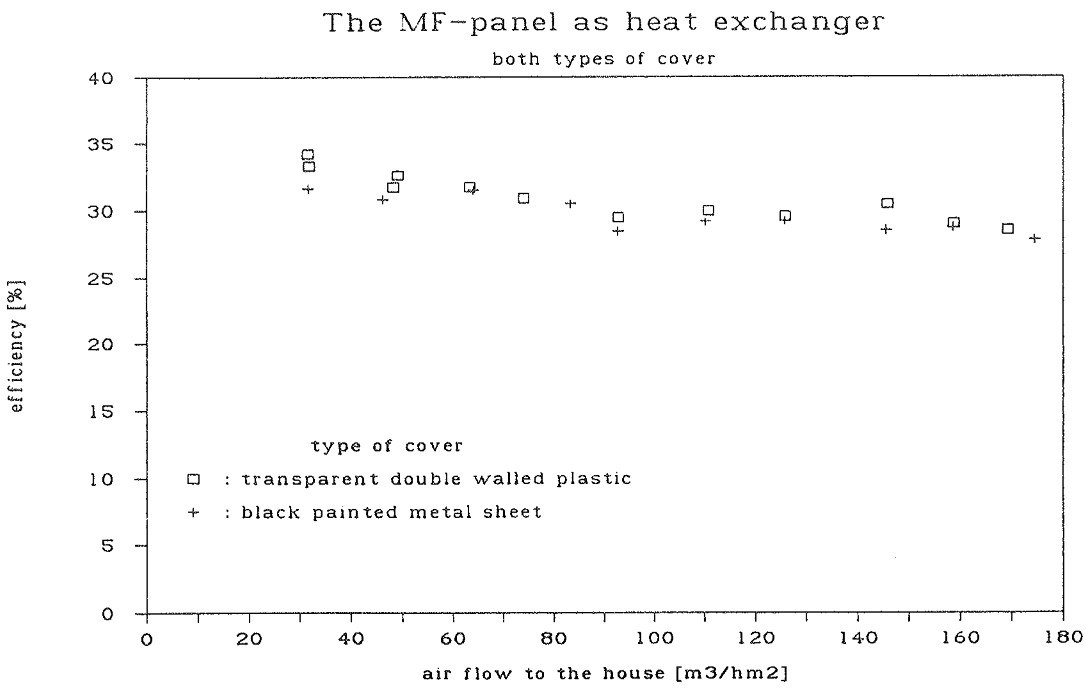

Figure 1.4. The results from tests on the MF-panel working as a heat exchanger between fresh air and exhaust air.

For design conditions (ambient temperature: -12°C and inside temperature: 20°C) the MF-panel will reduce the heat loss through the wall or roof by 89%.

Simulations have shown, that the performance of the MF-panel is very high. Depending on the area, the flow rate and the energy demand of the building the annual performance will be between 250 and 1350 kWh/m^2.

A more detailed description of the results from the above-mentioned research work can be found in (Jensen, 1990a) or in appendix A. Appendix A contains a paper to the symposium "Building Physics in the Nordic Countries", Trondheim, Norway, August 20-22, 1990 (Jensen, 1990b).

The encouraging results from the R&D project inspired the project group behind the MF-panel concept to test the concept on a real building exposed to real climate conditions and user behaviour. A proposal for a demonstration project was, therefore, submitted to the CEC in 1987. The idea was to install about 200 m^2 in connection with the construction of a large shopping and conference centre in Næstved in the southern part of Zealand. The project was accepted by the CEC. Due to problems within the construction group of the centre, the installation of MF-panels was, however, cancelled. In order to realize the demonstration project a search for another suitable building was performed. It was decided to transfer the demonstration project to a building at Wewer's Brickyard in Helsinge (in the northern part of Zealand). The CEC accepted this change in the project. The building was not ideal for the purpose, but allowed the gain of valuable information concerning installation, cost and performance of the concept.

2. Description of the Building, the System and the Measuring System

The present section contains a description of the building and its use together with a description of the MF-system and the measuring system.

2.1. The Building

The building is located at Wewer's Brickyard in Helsinge (in the northern part of Zealand). The brickyard manufactures traditional bricks for the building industry, a major part of the bricks are for export. The building, where the MF-panel is installed, contains a workshop for manufacturing brick beams and special-purpose bricks.

Figure 2.1 shows a drawing of the building with the approximate location of the MF-panel. Figure 2.2 shows a plan of the rooms of the building. The building has uninsulated brick walls and single pane windows. The roof is poorly insulated with only approximately 50 mm poorly located mineral wool batts. The main entrance to the building is through a leaky sliding wooden door (the barn door type) to room 1 - se also figure 2.7. Also the gates to room 3 and 5 allow a high degree of natural infiltration. The building has thus a very high heat loss both due to transmission and to natural infiltration.

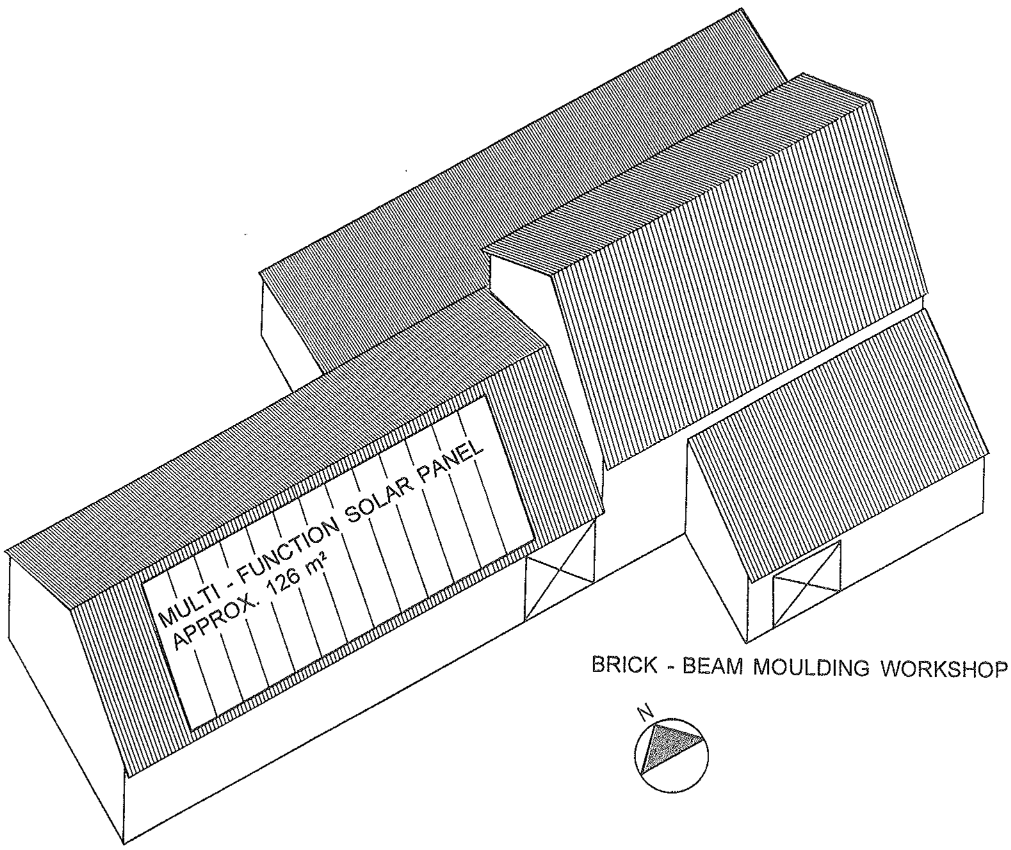

Figure 2.1. The workshop with the approximate location of the MF-panel.

The orientation of the MF-panel is due south and the tilt is 19°.

Brick beams are manufactured in both room 1 and 2. In room 2 the brick beams are handled in a semi-automatic way. Special-purpose brick beams are manufactured on working tables in room 1. The production of the special-purpose bricks is also located in room 1. Room 3 is a cutting room, where the grooves for the steel reinforcement are cut. Room 4 serves as "office", area for breaks and production place for demonstration plates showing the bricks manufactured at the brickyard. The gas boiler is located in this room. The mixing machine is located in room 5.

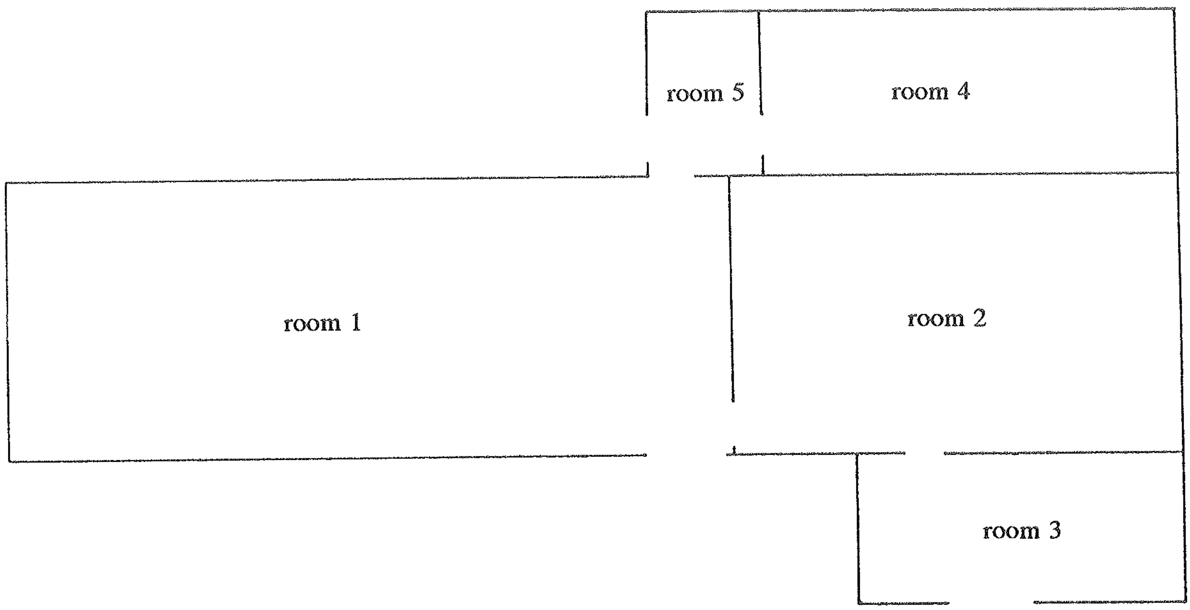

Figure 2.2. The rooms of the workshop.

Figures 2.3-5 show photographs from room 1 and 2, while 2.6 shows the gas boiler of the traditional heating system of the building. The idea of installing the MF-system in the workshop was to improve the working conditions for the workers and to decrease the drying time for the brick beams. The working conditions could be improved by increasing the room temperature and by a decrease of the humidity of the rooms. The decrease of the humidity would also decease the drying time for the brick beams.

However, during the construction phase (1990-91) several changes were introduced within the brickyard. The brickyard was together with other brickyards taken over by another company. One of the brickyards was closed down and part of the production was transferred to Wewer's Brickyard - among other things the production of special-purpose bricks for English manors. These special-purpose, handmade bricks have to dry out very slowly. So the idea of decreasing the humidity using the heat exchanger function of the MF-panel had to be dropped. During the measuring period the workers did during several periods, for the same reason, turn off the inlet of solar heated air to room 1. So the building became during the construction phase less applicable for the demonstration of the MF-panel. However, at that time it was too late to change the plans. In order to overcome this it was decided to carry out special-purpose measuring experiments instead, where the system was forced to operate in specific ways in order to maximize the obtainable information of the different ways of operation for the MF-panel.

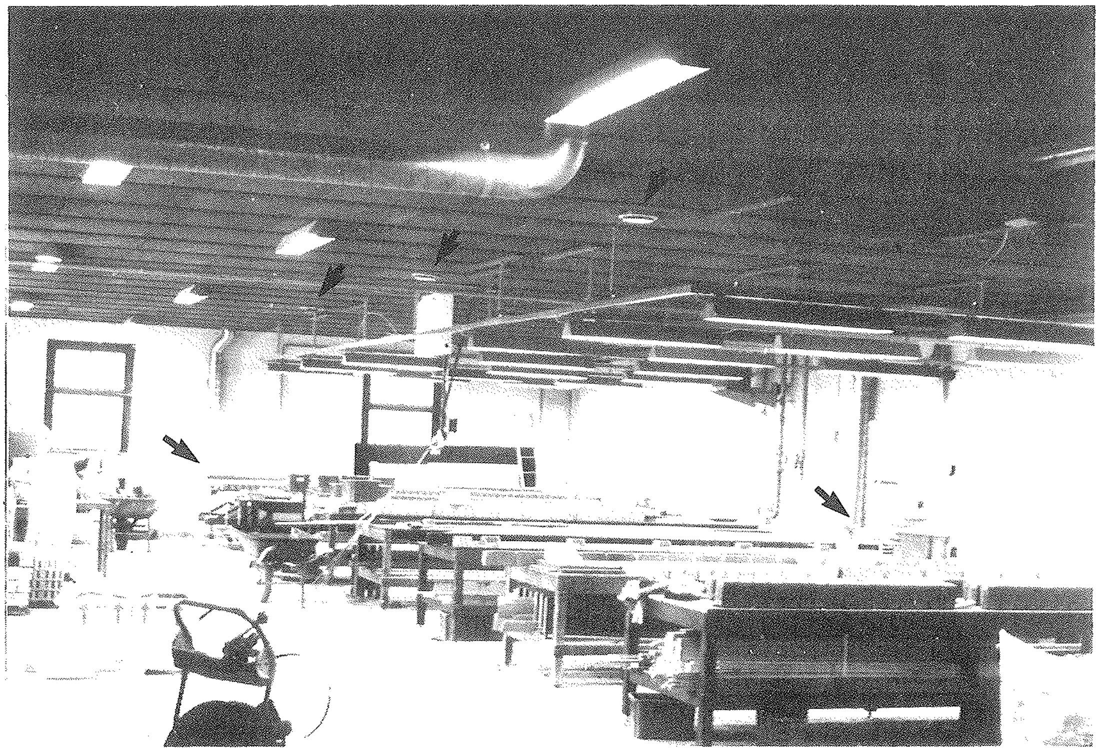

Figure 2.3. Room 1 with the working tables for manufacturing of special-purpose brick beams and bricks.

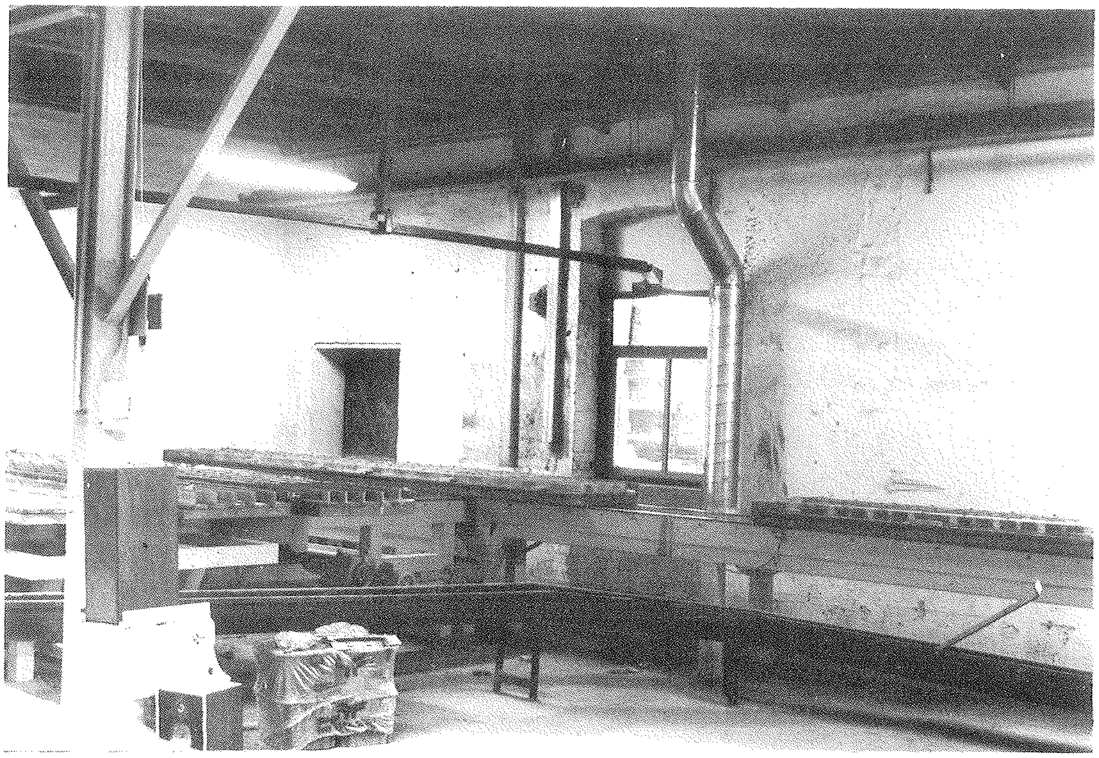

Figure 2.4. Room 2 with the semi-automatic systems for handling the brick beams.

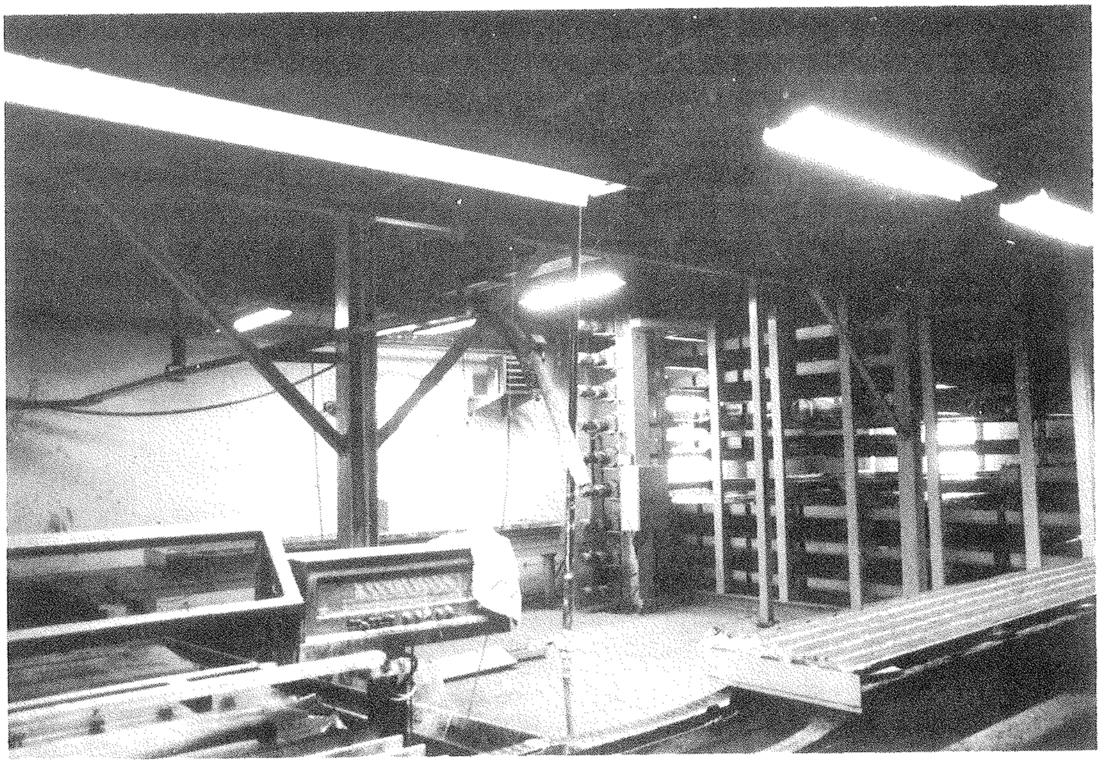

Figure 2.5. Room 2 with the semi-automatic system for handling and storing the brick beams during the drying-out period.

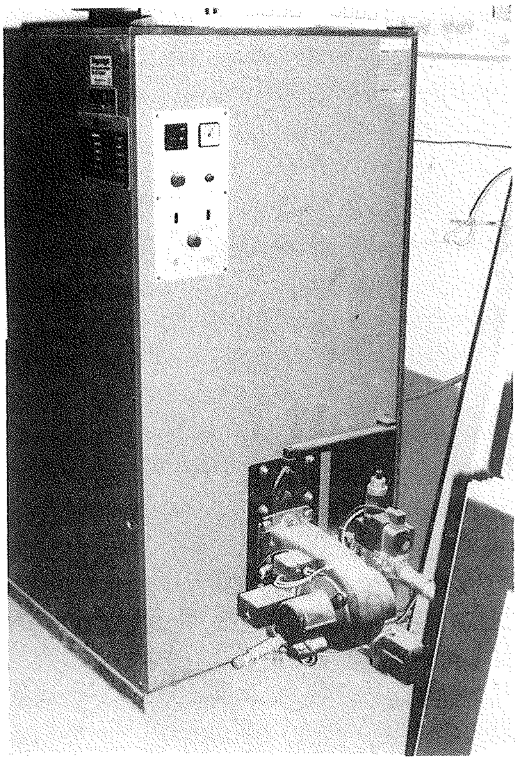

Figure 2.6. The gas boiler of the traditional heating system of the building located in room 4.

2.2. The System

The actual MF-panel system is described in this section. The description is divided into three paragraphs describing the MF-panel, the ducting and the control of the system.

2.2.1. The MF-panel

Based on the results from the previous R&D project it was decided that the cover of the MF-panel for the demonstration project should be a transparent double walled ribbed plastic cover, as the performance of this configuration had shown to be higher than with a black metal plate. The cover is, as for the prototype, made of UV-protected polycarbonate. The UV-protection is a thin layer of acrylic on the outer surface of the cover.

Analysis of the heat demand of the building showed that an MF-panel with an area of 200 m^2 would be too large. It was, therefore, decided to decrease the area of the panel to 126 m^2. The overall design for the MF-panel is based on the findings in (Jensen, 1990a) - please see this report for details - however, the precise area and dimension of the MF-panel is based on an optimization of the material of the panel - especially the length and width of the cover and the trapezium plates were determinating factors when designing the MF-panel.

One of the functions of the MF-panel is that it forms the wall or the roof of a building. So ideally the MF-panel should be installed in connection with the erection of the building or during a retrofit of the building as the MF-panel could then replace the traditional wall or roof which would lead to a lower extra cost for the MF-panel. This was, however, not possible at the workshop at Wewer's Brickyard as the roof did not need to be replaced. But it was judged that it would be possible to extrapolate the cost of the actual MF-panel to a situation where it is replacing a traditional wall or roof.

Figure 2.1 shows the approximate location of the MF-panel on the workshop, while figure 2.7 shows the MF-panel after installation on the roof.

Figure 2.8 shows the construction drawing of the MF-panel. The area of the MF-panel is approximately 6×21 m^2 = 126 m^2. The cover of the MF-panel is divided into 26 sections each with a width of 0.81 m. The trapezium plate is 0.5 m longer than the cover - see also figure 2.9. This is mainly due to the obtainable length of these plates. However, this has been utilized to serve two purposes: 1) the mixing of in- and outgoing air is to a large extent prevented - see figure 2.10, 2) the temperature increase of the incoming air is very small during the first 0.5 m, which results in a nearly zero heat loss, so removing the cover on this part does not much increase the heat loss from this end of the MF-panel - at least less than the increase of absorbed solar energy due to the higher transmittance of solar radiation, ie a 100% transmittance due to the missing cover.

The MF-panel is a bit longer than the roof (going over the roof ridge) as seen on figure 2.11.

The MF-panel is fastened to the existing roof via a wooden lath skeleton as seen on figure 2.8 and figures 2.12-13. On this skeleton plates of chipboard were located in order to form the back of the MF-panel and to create a stable plane for the backside insulation - see figure

2.14. At the top of the skeleton behind the two manifolds, mineral wool was placed under the chipboard in order to form the backside insulation of the manifolds - figures 2.8 and 2.15.

Figure 2.7. The workshop with the MF-panel.

On the chipboard a new skeleton of wooden laths was placed in order to maintain the backside insulation in position and for carrying the trapezium plates. This skeleton is shown on figures 2.16-17.

The backside insulation, made of 75 mm mineral wool batts, is located on the chipboard between the laths. In order to protect the insulation from any condensation, a plastic foil is located on top of the insulation. The backside insulation with the plastic foil is shown on figures 2.18-19 together with the trapezium plates and the two manifolds. The trapezium plates are mounted on the laths on 10 mm wooden lists in order to create a small distance between the trapezium plates and the backside insulation, in order to increase the heat transfer between the two air streams.

Figures 2.18-19 also show the separation between the two manifolds. This separation is made of foam rubber chocks. It is very important that the separation between the two manifolds is absolutely air tight in order to prevent any shortcut between the two air streams. The solution for the separation of the two manifolds has also been applied in the inlet to the lower manifold - the manifold for the outlet air. But the top of the foam rubber chocks has been cut away as shown on figures 2.18-19. The reason for this is to create a rather large pressure drop at the inlet to the MF-panel from the outlet manifold in order to create an even air stream all under the trapezium plates. The foam rubber chocks reduce the cross section of the inlet to the MF-panel from the manifold to only the half of the cross section under the trapezium plate.

Figures 2.18-19 further show two of the in- and outlet ducts to the ventilation system.

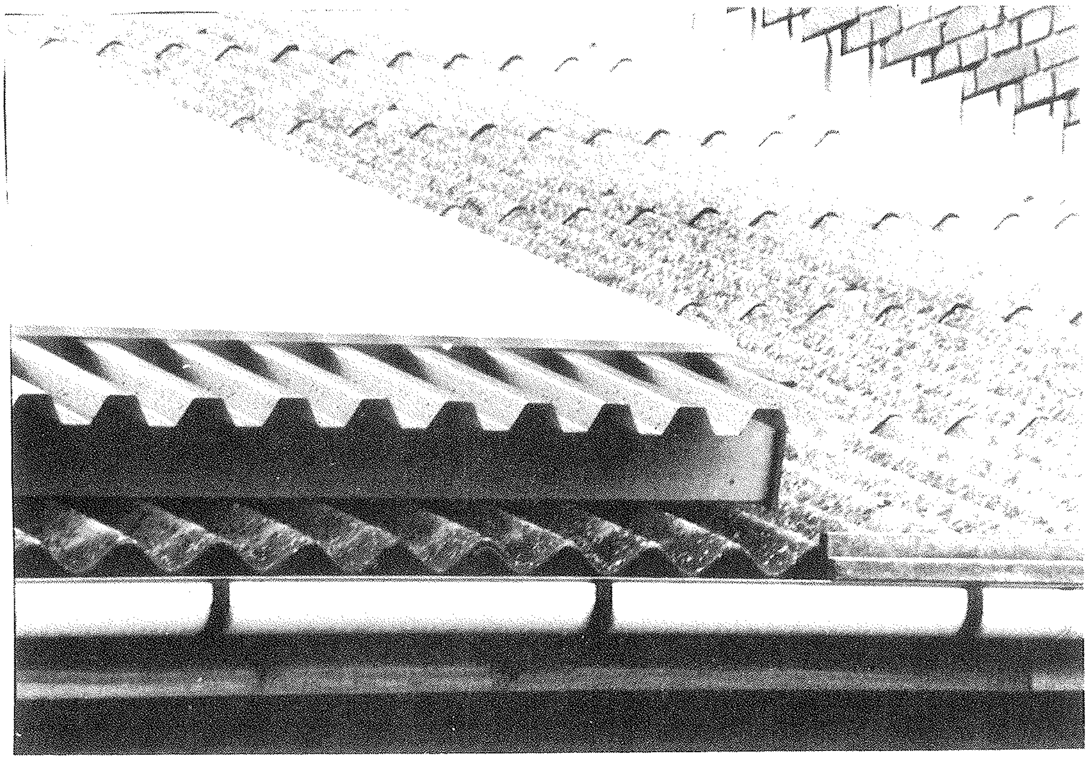

Figure 2.9. The bottom of the MF-panel. The trapezium plate is longer than the cover.

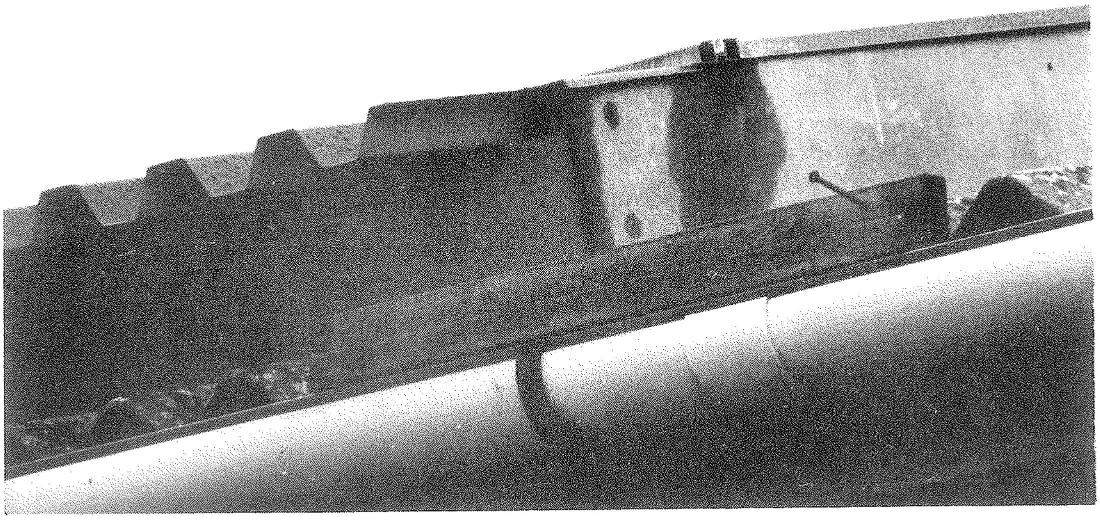

Figure 2.10. The trapezium plate is longer than the cover and also longer than the back-side insulation. This will decrease the risk of mixing of the incoming air with the outgoing air.

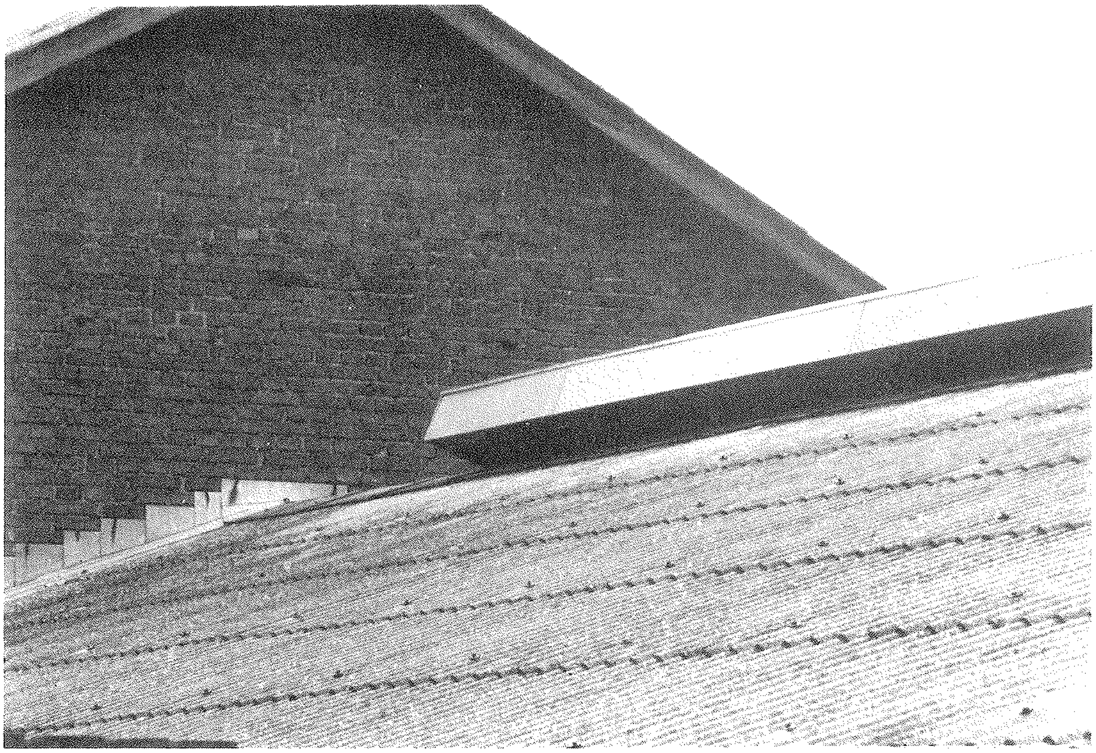

Figure 2.11. The top of the MF-panel. The MF-panel is longer than the roof.

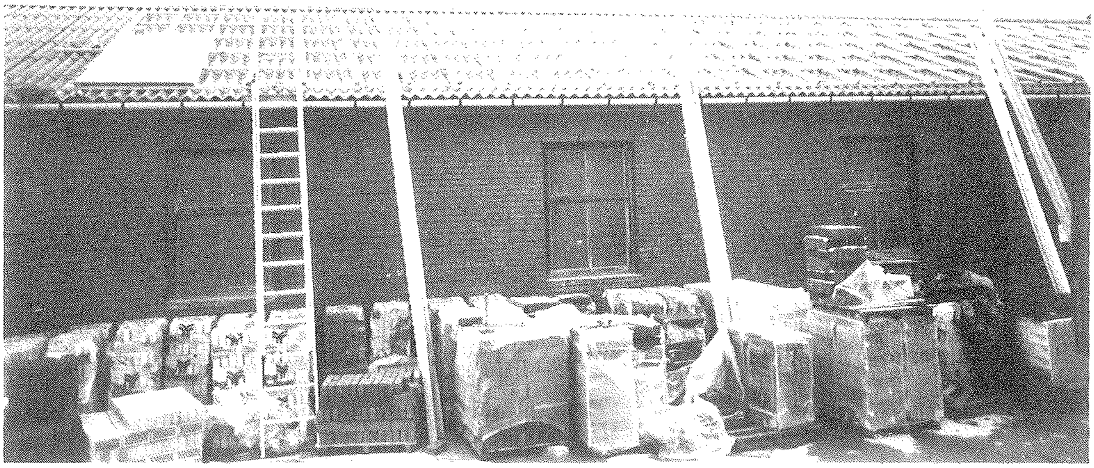

Figure 2.12. The wooden skeleton for securing the MF-panel to the existing roof.

Figure 2.13. Close-up of the skeleton for securing the MF-panel to the existing roof.

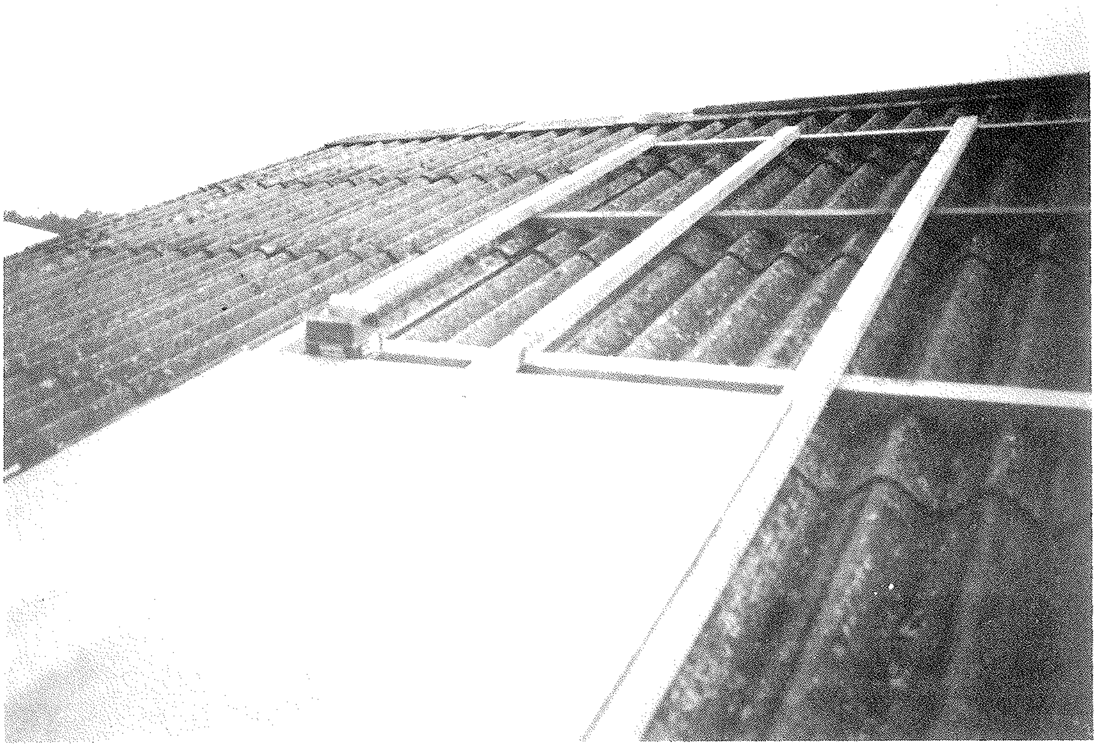

Figure 2.14. The backside protection of the MF-panel made of chipboards mounted on the wooden skeleton.

Figure 2.15. The backside insulation of the manifolds located in the wooden skeleton under the backside chipboards.

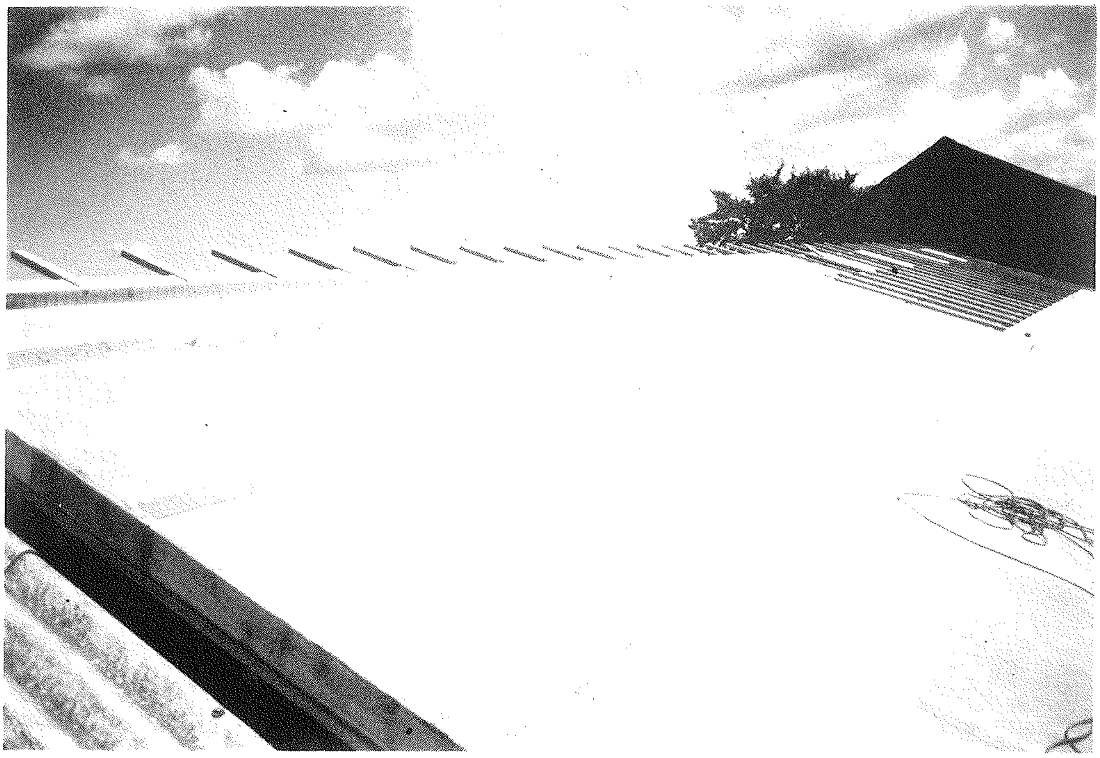

Figure 2.16. The wooden skeleton for maintaining the backside insulation in position and for carrying the trapezium plate.

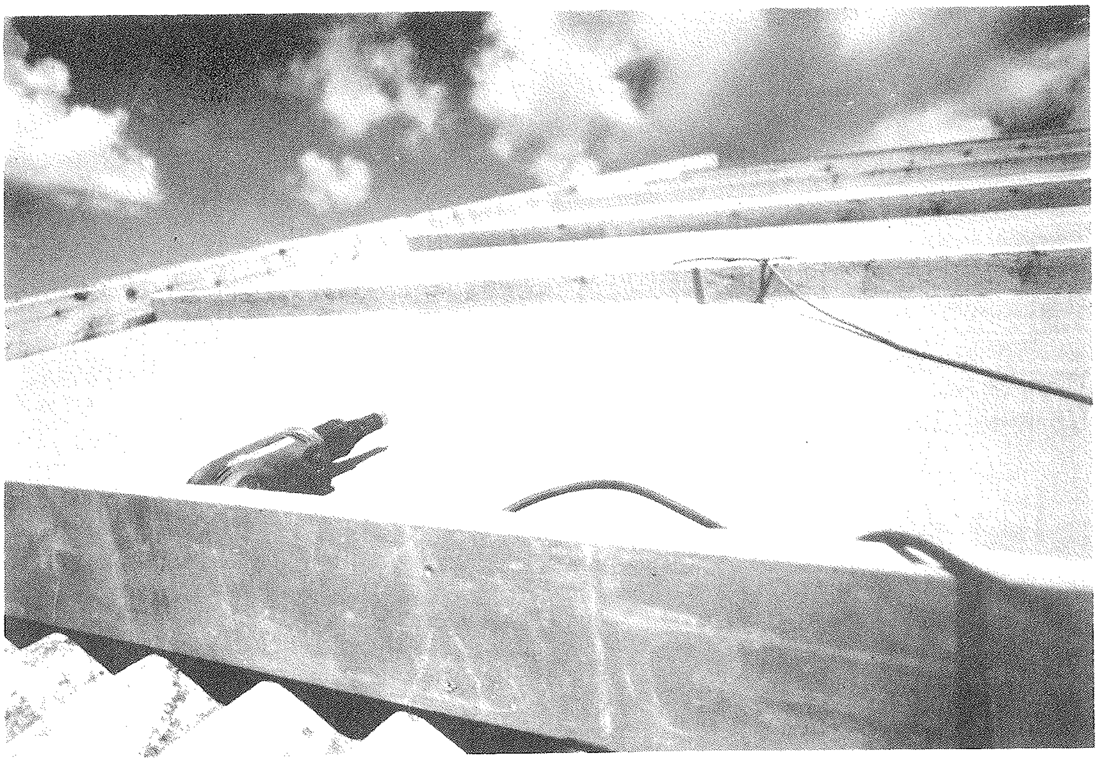

Figure 2.17. Close-up of the wooden skeleton for maintaining the backside insulation in position and for carrying the trapezium plate.

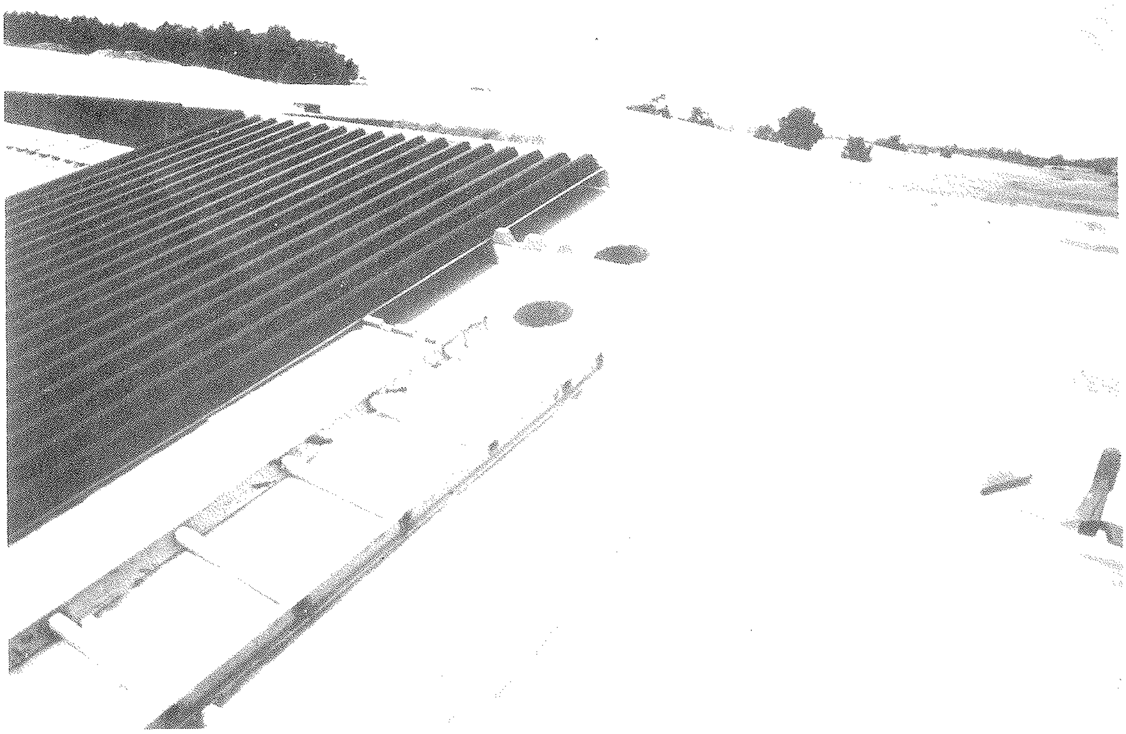

Figure 2.18. The backside insulation, trapezium plate and the manifolds of the MF-panel.

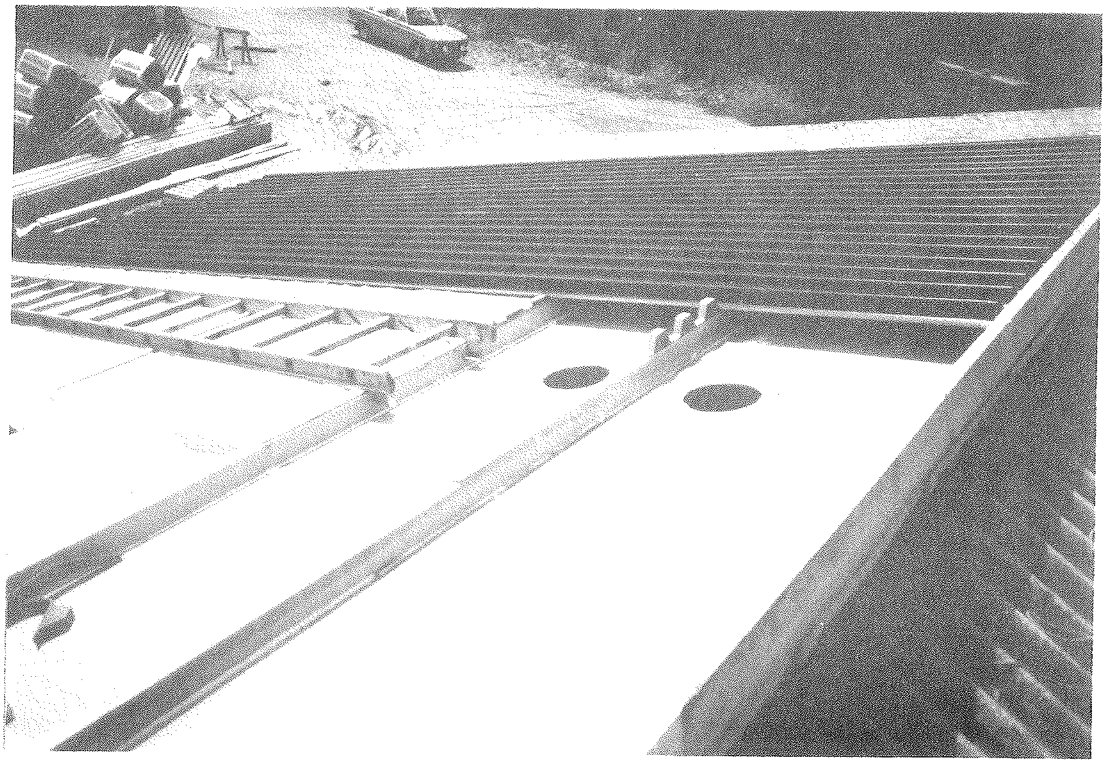

Figure 2.19. The backside insulation, trapezium plate and the manifolds of the MF-panel.

The absorber of the system was made of trapezium corrugated steel plates with a black surface, from Robertson. The chosen profile was as for the prototype the BR 45 profile shown in figure 2.20.

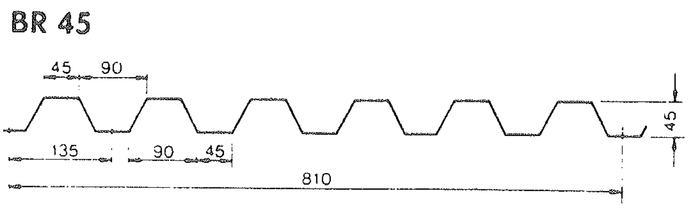

Figure 2.20. The profile of the trapezium corrugated steel plates used as absorber in the MF-panel at Wewer's Brickyard.

Figures 2.21-22 show the mounting of the trapezium plates. In order to prevent any shortcut between the incoming and outgoing air stream, the joints between the trapezium plates were carefully sealed as shown in figures 2.21-22.

In order to create an even distribution of the incoming air over the absorber a pressure drop was created at the top of the MF-panel at the manifold. The trapezium plate was not stopped at the manifold but was continued almost to the top of the manifold as shown in figures 2.8 and 2.23-24. Only an air gap of 15-20 mm was left for the air to flow into the manifold.

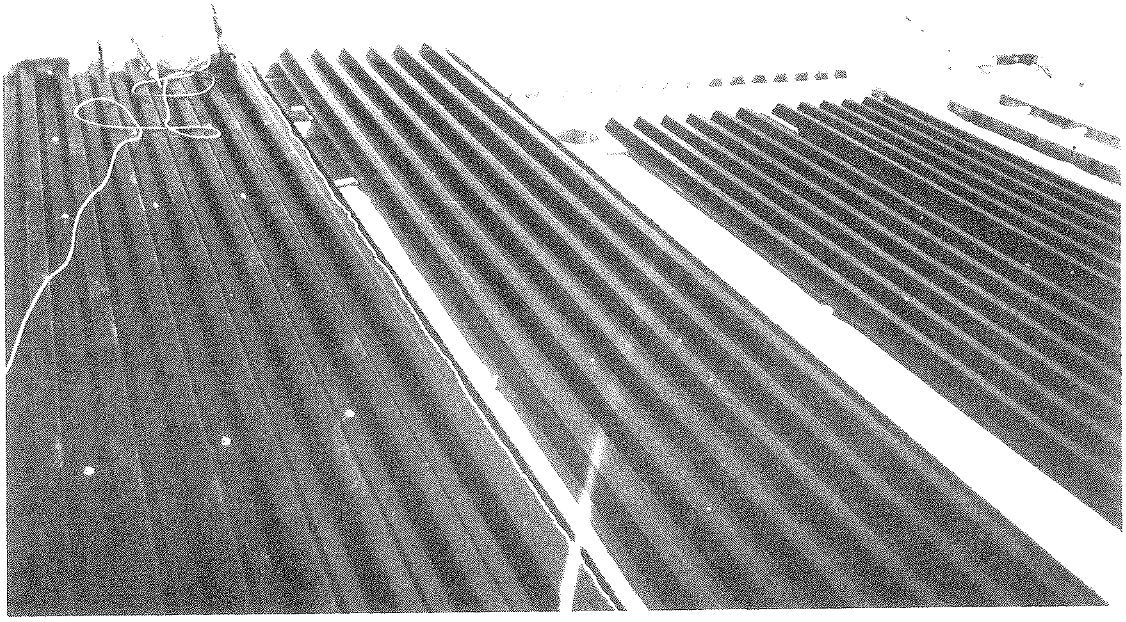

Figure 2.21. The installation of the trapezium corrugated absorber plates.

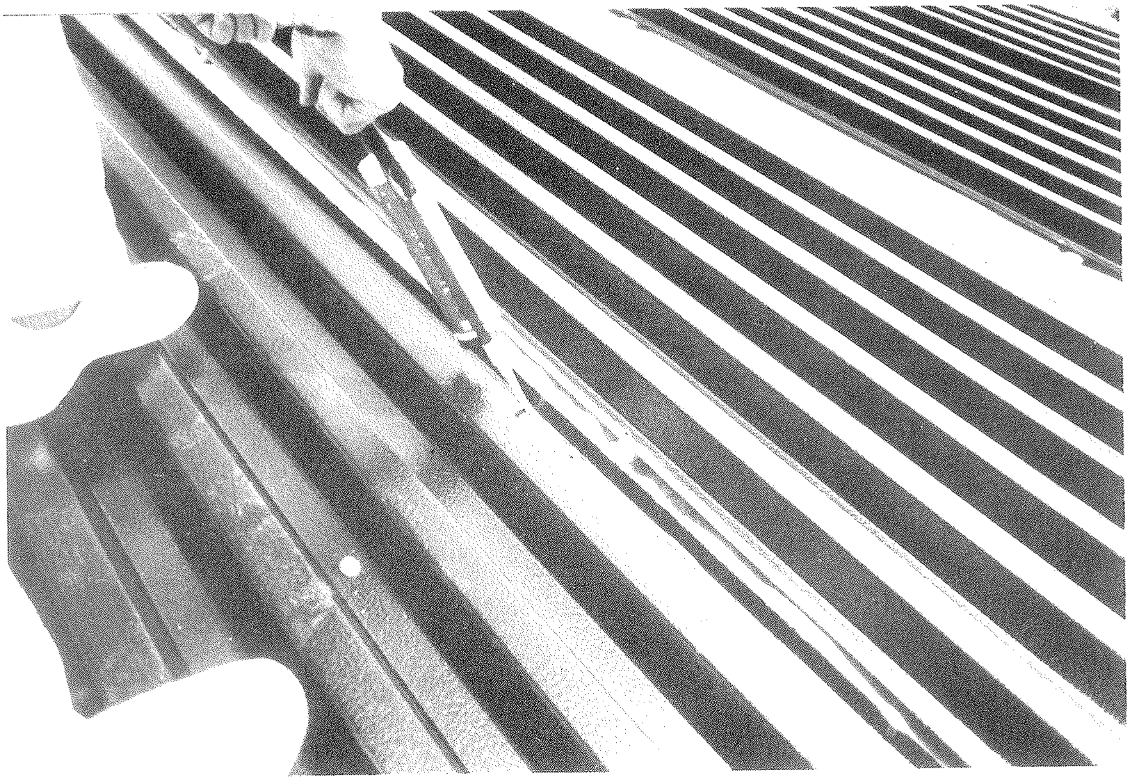

Figure 2.22. The joint between the trapezium corrugated absorber plates was carefully sealed.

Figure 2.23. The top of the MF-panel showing the air gap to the manifold at the top of the absorber.

The cover is made from double-walled 10 mm thick ribbed polycarbonate plates. The cover is fixed to the MF-panel by means of aluminium profiles as shown on figure 2.25 (not shown on figure 2.8). The profiles lift the cover 10 mm above the absorber. However, during operation as solar collector the cover will be heated up and expand. As air is sucked in through the channel between the absorber and the cover, the cover will be sucked into contact with the absorber. This will as shown in (Jensen, 1990a) decrease the performance of the MF-panel and will furthermore probably lead to damage of the covers when getting in contact with the very hot absorber. Therefore, spacers have been located with regular intervals (approximately one per 300 mm). The spacers were made of screws with a metal and a plastic washer as shown in figure 2.26. The spacers maintain a minimum distance between the absorber and the cover of 5 mm.

The cover is fixed to the panel by means of a 50 $\times$ 5 mm aluminium profile fastened to the profile shown in figure 2.25. In order to obtain an air tight cover, sealing strips were placed between the cover and the top aluminium profile.

On figure 2.25 it is indicated that the top profile normally would have been plastic profiles which are clicked together with the aluminium profile. Actually the carpenter installing the MF-panel did at first, on his own, use such plastic profiles. But during a heavy storm one of the cover plates was blown of - see section 4. The plastic profiles were, therefore, replaced with the here described aluminium profiles and fastened to the panel by means of screws.

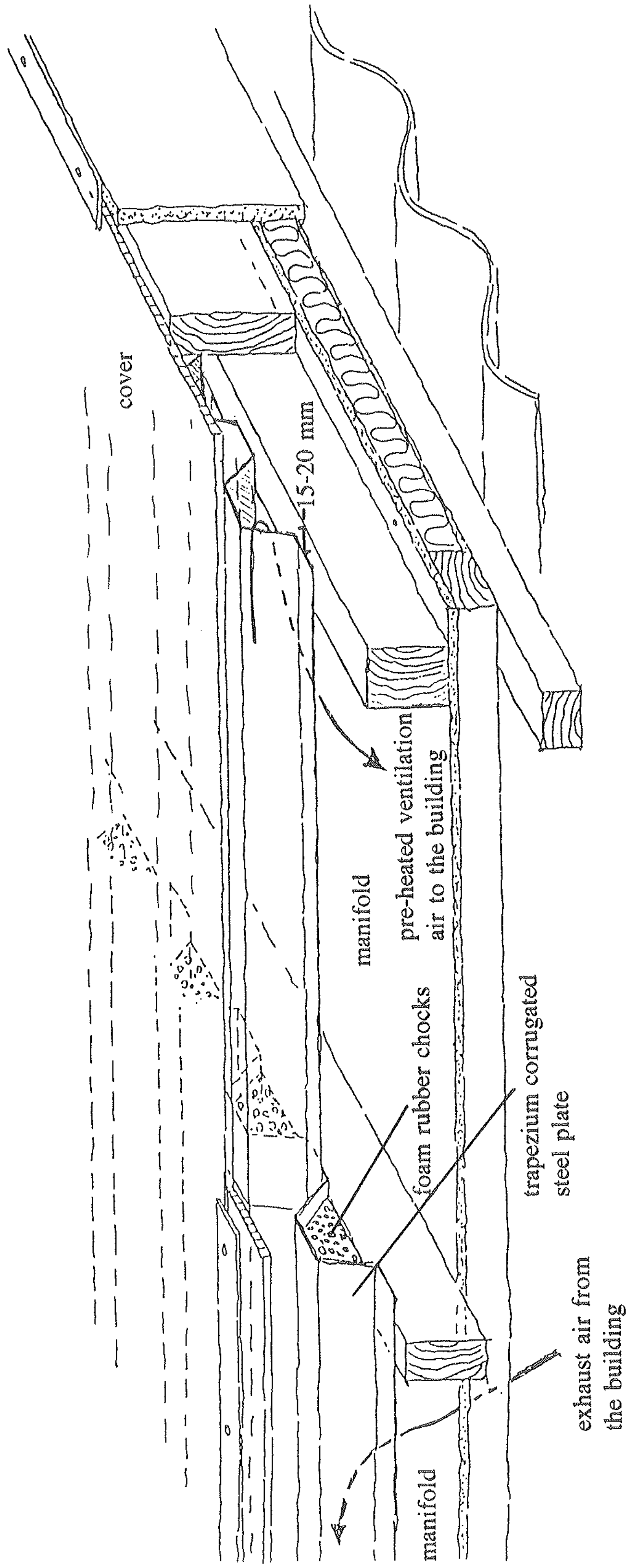

Figure 2.24. The top of the MF-panel showing the air gap between the channel between the cover and the absorber and the manifold. The figure does not show the distance between the insulation and the absorber and the absorber and the cover.

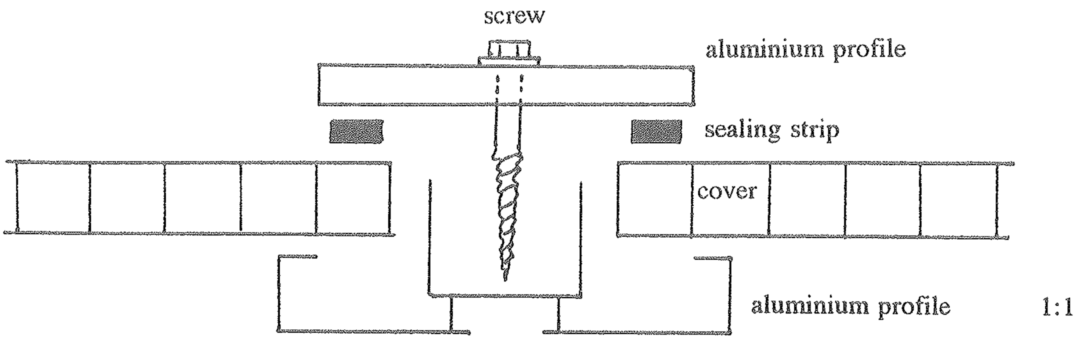

Figure 2.25. The profiles for fastening the cover to the panel.

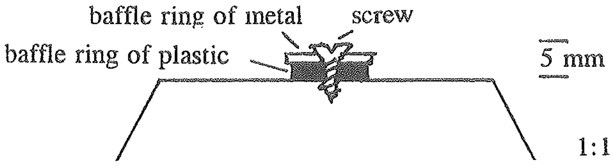

Figure 2.26. The spacers between the absorber and the cover located on the trapezium corrugated plate in between the above-shown profiles.

Figure 2.27 shows the MF-panel after installation.

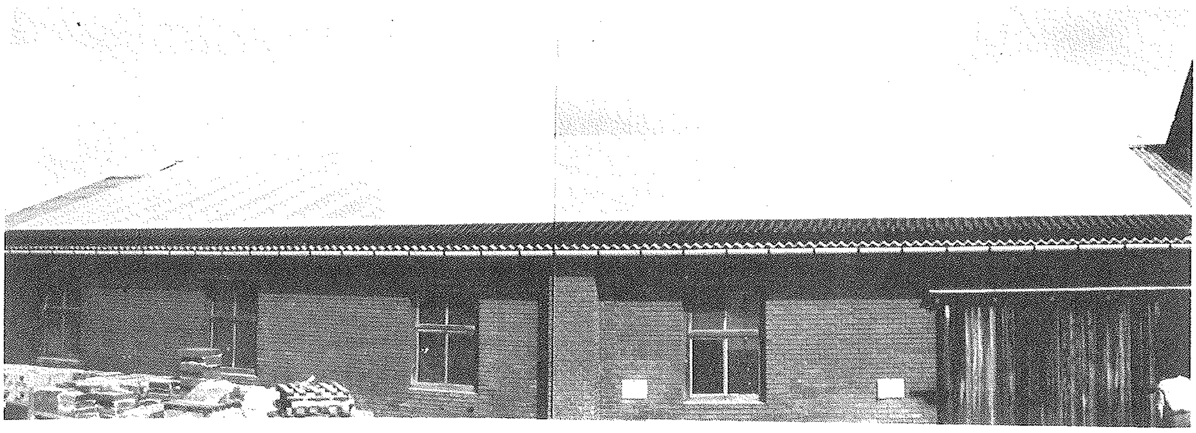

Figure 2.27. The MF-panel after installation. The figure is made by combining two photographs.

2.2.2. The Ducting

The MF-panel serves both as a solar air collector and as a heat exchanger between fresh air to the building and exhaust air from the building. For that reason a pair of ducts between the MF-panel and the building is necessary.

Figure 2.8 shows that the MF-panel is connected to the ducting system via 9 pairs of channels. Figure 2.28 shows the location of the MF-panel relative to the plan of the building. Room 1 and room 2 have fairly similar volumes - 840 and 645 m^3 respectively, while the volume of room 3 is much smaller - 180 m^3. It was, therefore, decided to connect approximately 56 m^2 of absorber area = 4 pairs of ducts to each of the rooms 1 and 2, while room 3 was connected to the last pair of ducts - approximately 14 m^2 of absorber area. The gas boiler is located in room 4, so it was decided not to connect any part of the MF-panel to this room as the room is heated by the heat loss from the boiler. The ducts to the rooms are insulated with 30 mm of mineral wool.

Figures 2.29-30 show how the MF-panel is connected to the three rooms. The MF-panel was installed on an existing building on the existing roof. The installation of the ducting has, therefore, been rather difficult. The precise location of the ducts has to some extent been determined by the location of the rafters in the attic - see figure 2.31.

The four pairs of ducts to room 1 (in 1-4 and out 1-4) have been led as separate ducts with a small fan in each string equal to 8 small fans for this room - figures 2.31-32 show one of these fans. The ducting system for this room has been made of ducts with a diameter of 200 mm. The inlet air is blown into the room through diffusers right under the ceiling, while the outlets are placed along the walls 1 m from the floor. In this way no shortcut exists between the inlets and outlets. Figure 2.30 shows the location of the inlets and outlets. Figure 2.3 shows some of the inlets and outlets of room 1 (at the arrows).

The four pairs of ducts to room 2 (in 5-8 and out 5-8) were collected into one pair of ducts with a diameter of 315 mm. Figure 2.33 shows the coupling of the ducts from the MF-panel to one pair of ducts - thus only two fans are necessary for this system. Figure 2.34 shows the two inlets in the attic over room 2. Figure 2.35 shows one of the two inlets to room 2. The room is rather high, so in order to get the heated air down to the workers no diffusers are located in these inlets. The outlets to the MF-panel are as for room 1 located along the walls 1 m from the floor. Figure 2.30 shows the location of the inlets and outlets to room 2.

Room 3 is only connected to the collector part of the MF-panel; it is thus not possible to exchange heat between fresh air and exhaust air for this room. The reason for this is that the infiltration of the room, due to many openings, is very large, so heat recovery is, therefore, less profitable. Only one small fan, identical to the fans used in the system of room 1, is installed here. The inlet to room 3 is on the back wall right under the ceiling as shown in figure 2.36.

During the summer-time with no heat demand the MF-panel will stagnate. In order to decrease the stagnation temperature three motor-driven bypasses have been installed. These bypasses will open when the temperature of the MF-panel becomes too high, allowing the MF-panel to be cooled by natural ventilation due to the stack effect. The location of the bypass ducts is shown in figure 2.28 and figure 2.37. The left upper corner of figure 2.31 shows one of the bypass ducts.

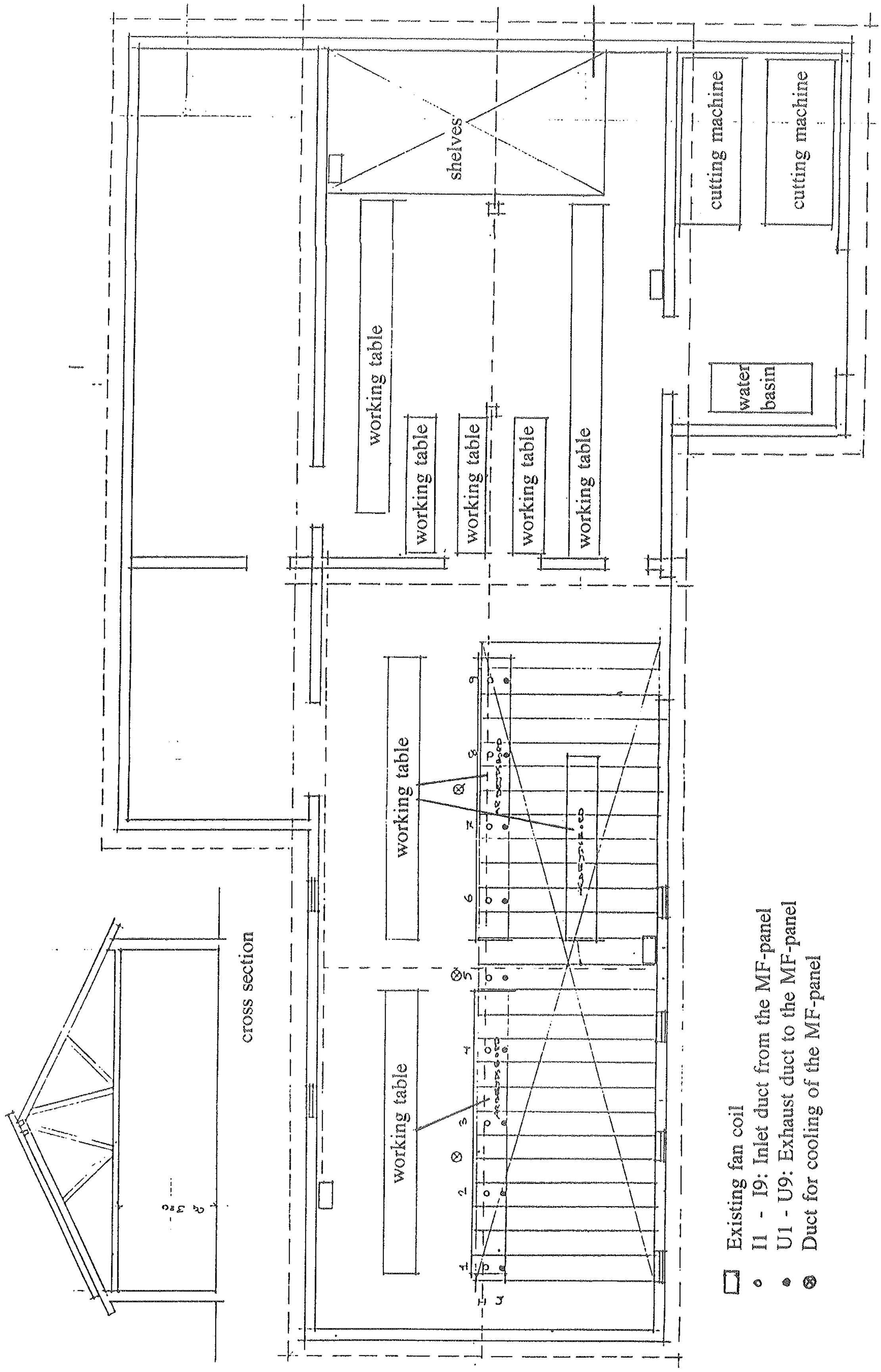

Figure 2.28. The location of the MF-panel relative to the plan of the building.

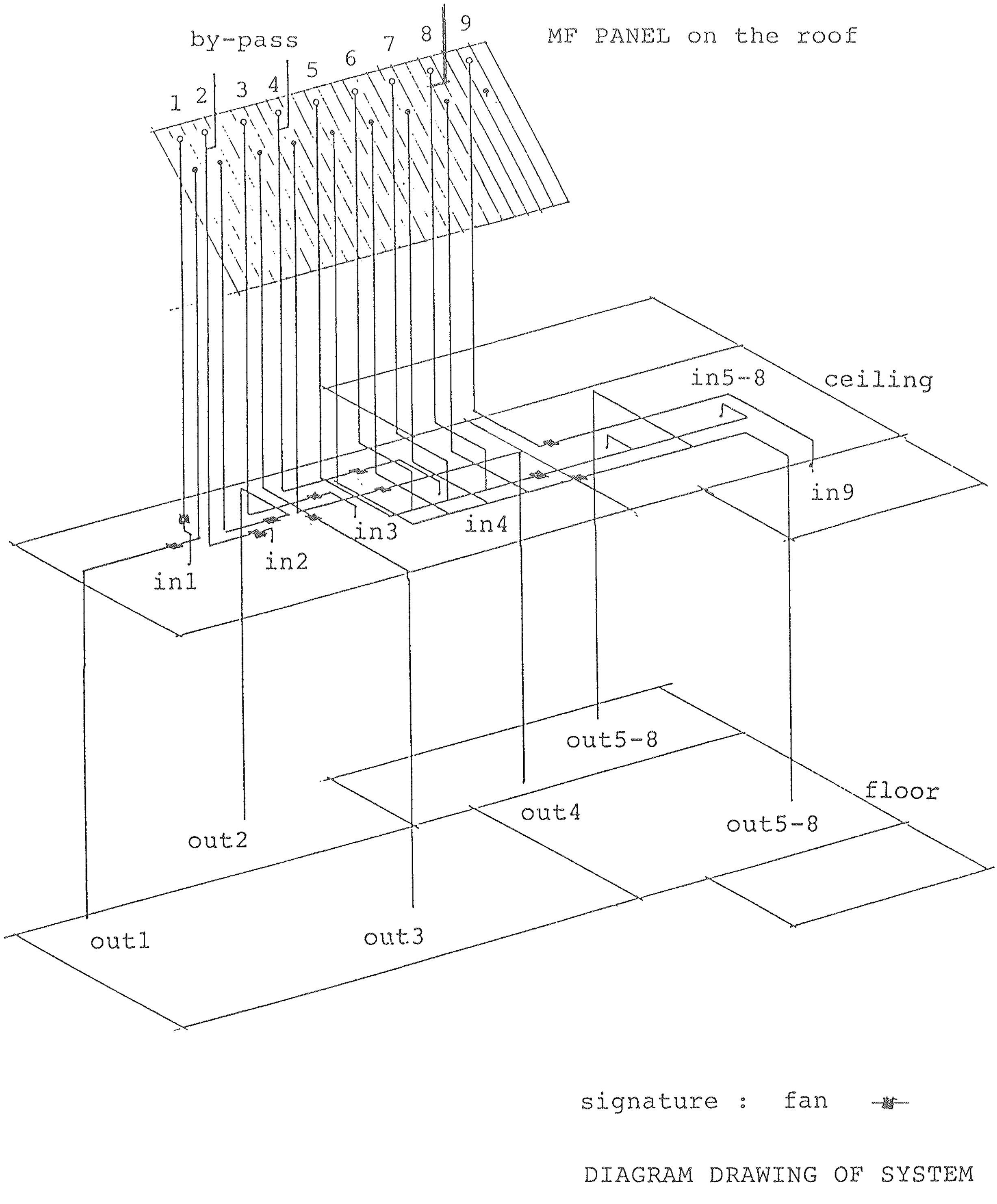

Figure 2.29. Isometric drawing of the connection between the MF-panel and the rooms of the building.

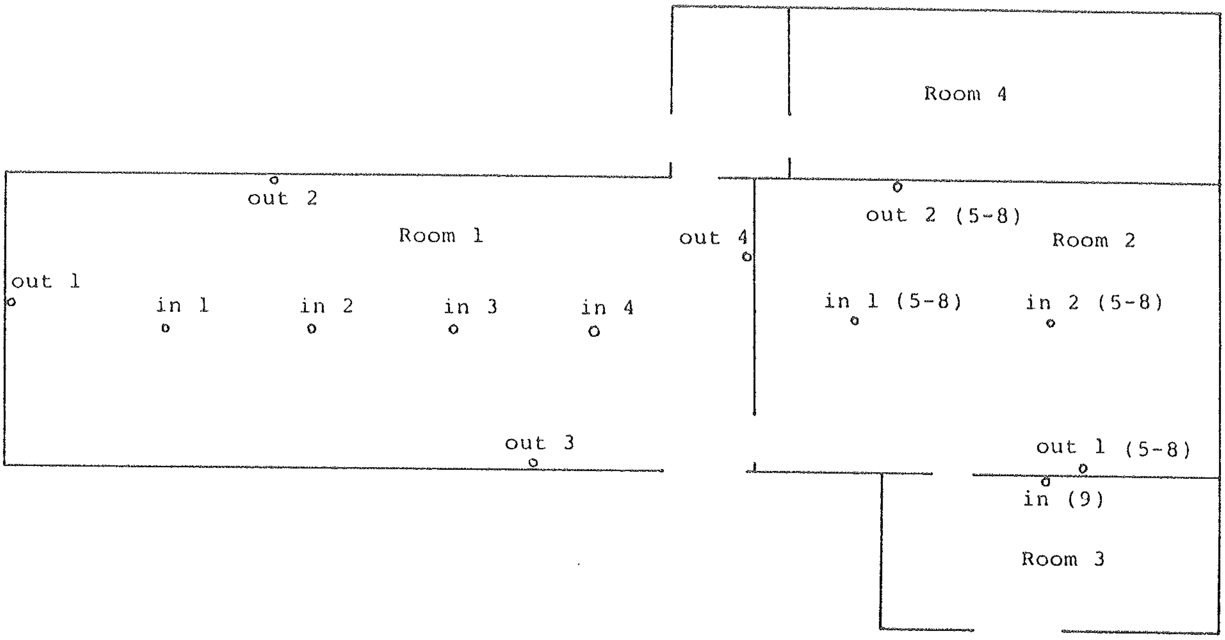

Figure 2.30. Plan of the brick-beam workshop showing air inlets and outlets from the MF-panel to the building.

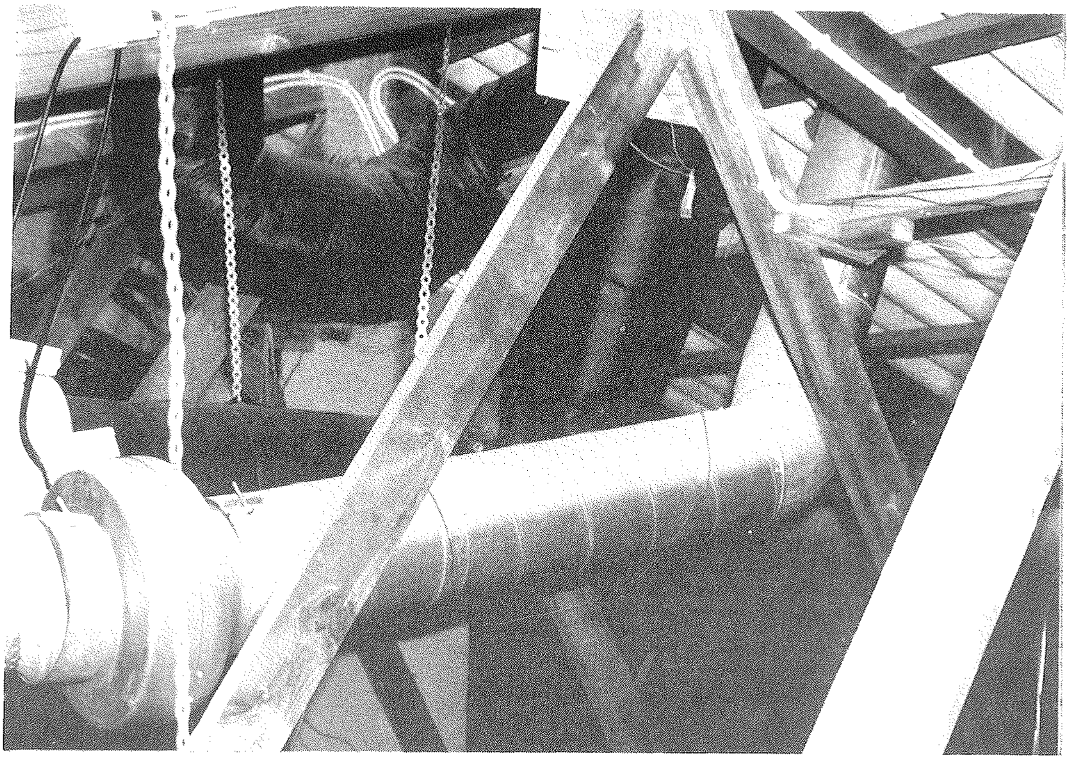

Figure 2.31. Photograph showing the rather difficult installation conditions in the attic of the workshop.

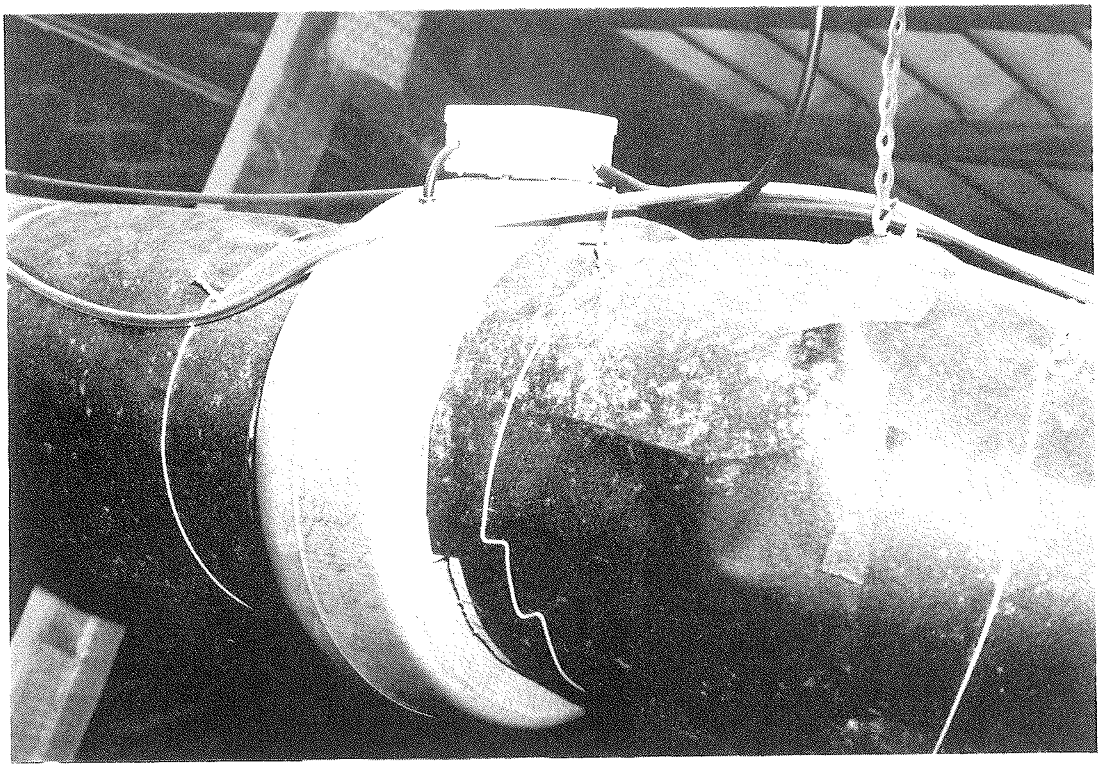

Figure 2.32. One of the fans in the ducting system for room 1.

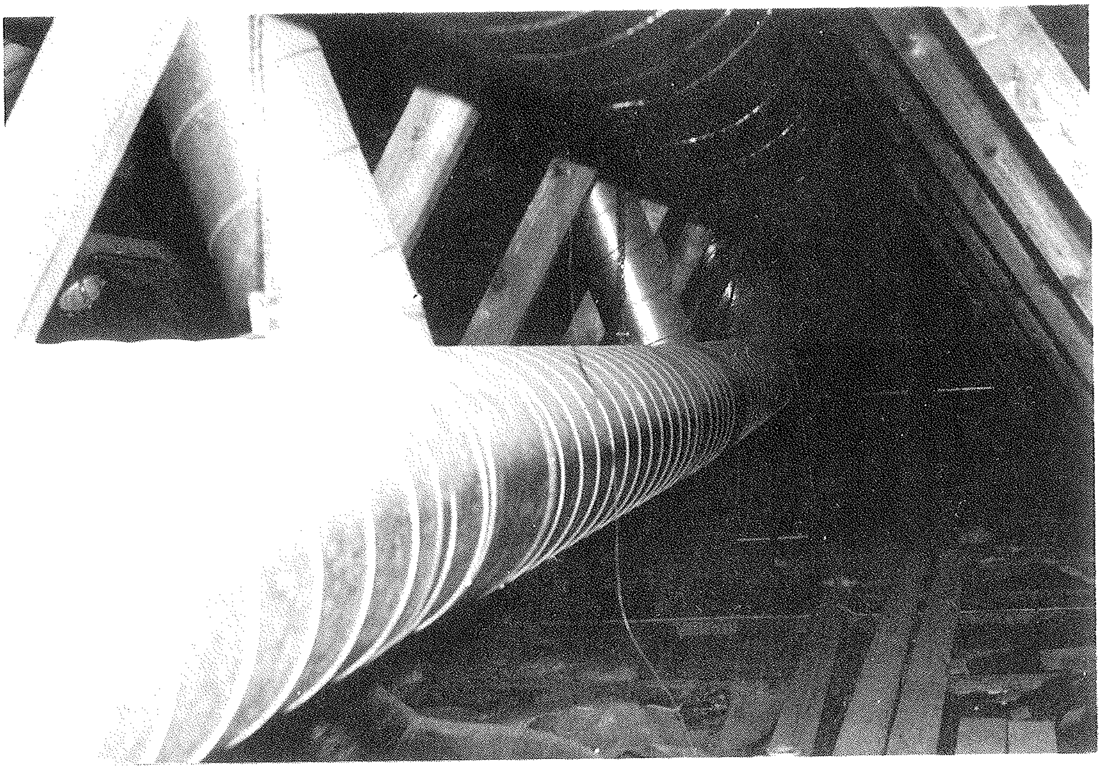

Figure 2.33. The coupling of the ducts from the MF-panel into one pair of ducts for room 2.

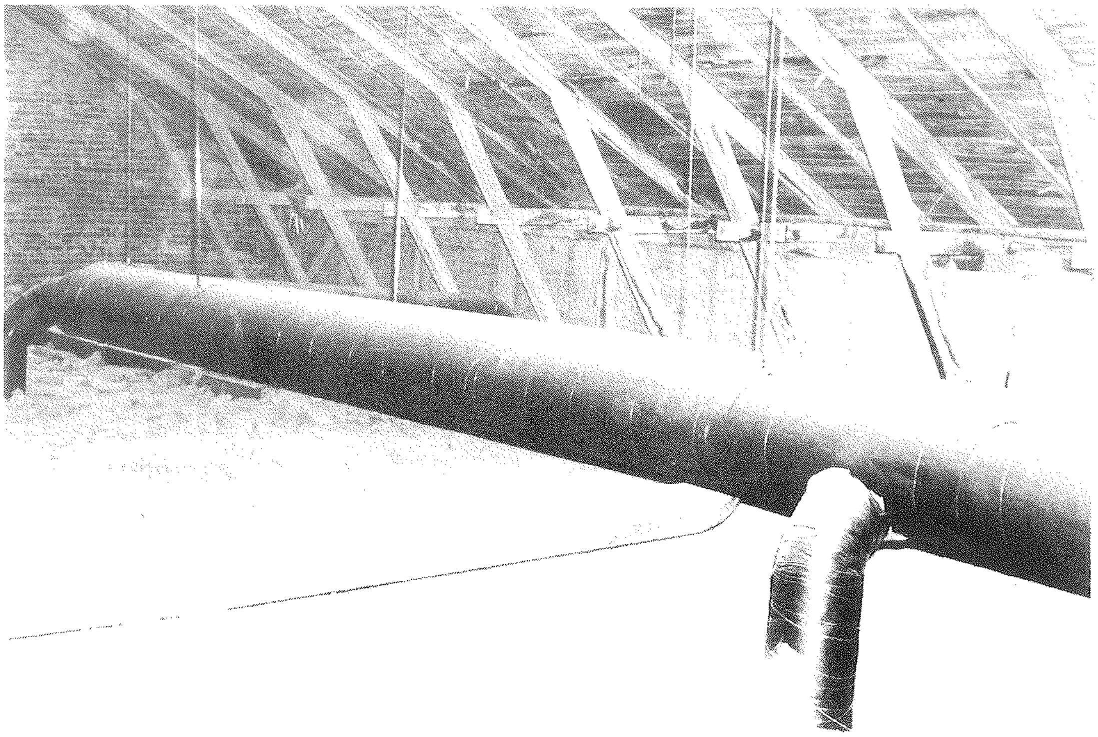

Figure 2.34. The attic over room 2 showing the inlets from the MF-panel to room 2.

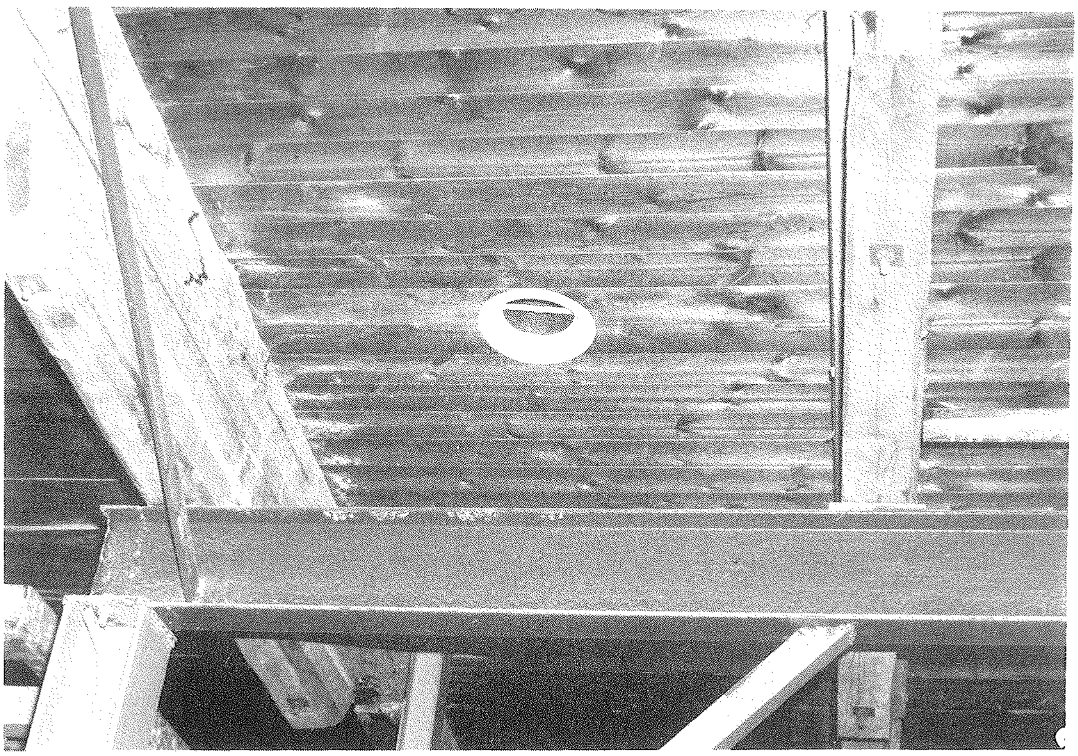

Figure 2.35. One of the inlets to room 2.

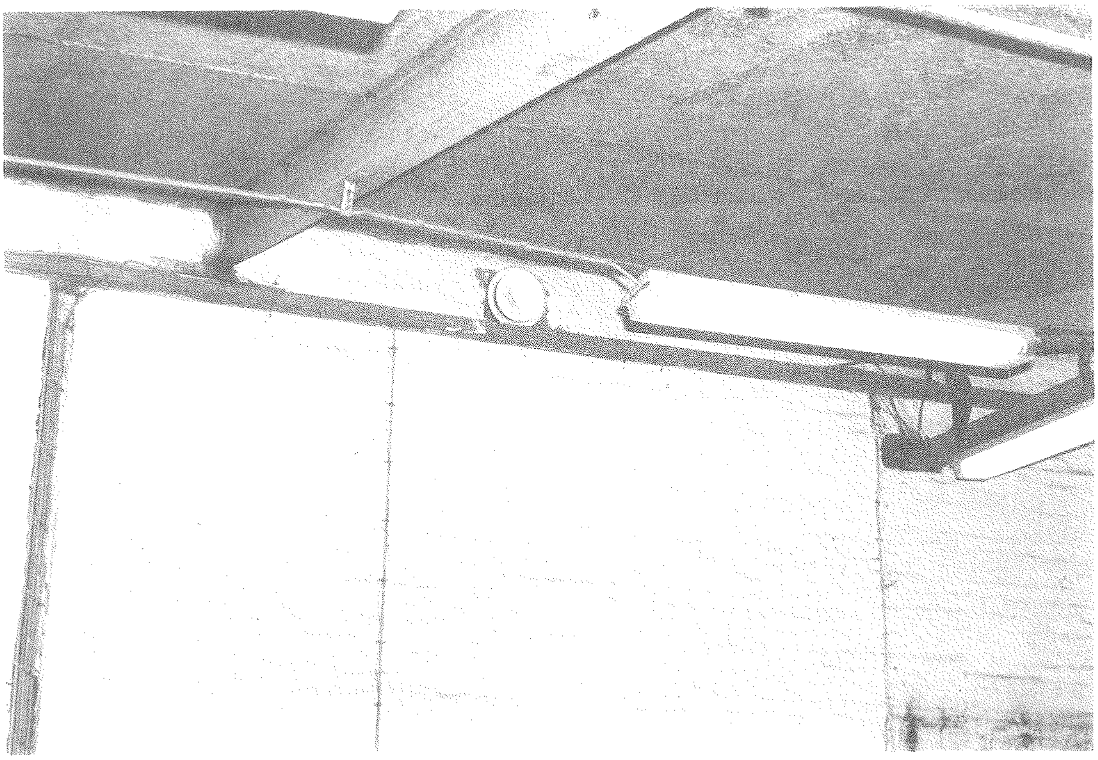

Figure 2.36. The inlet to room 3.

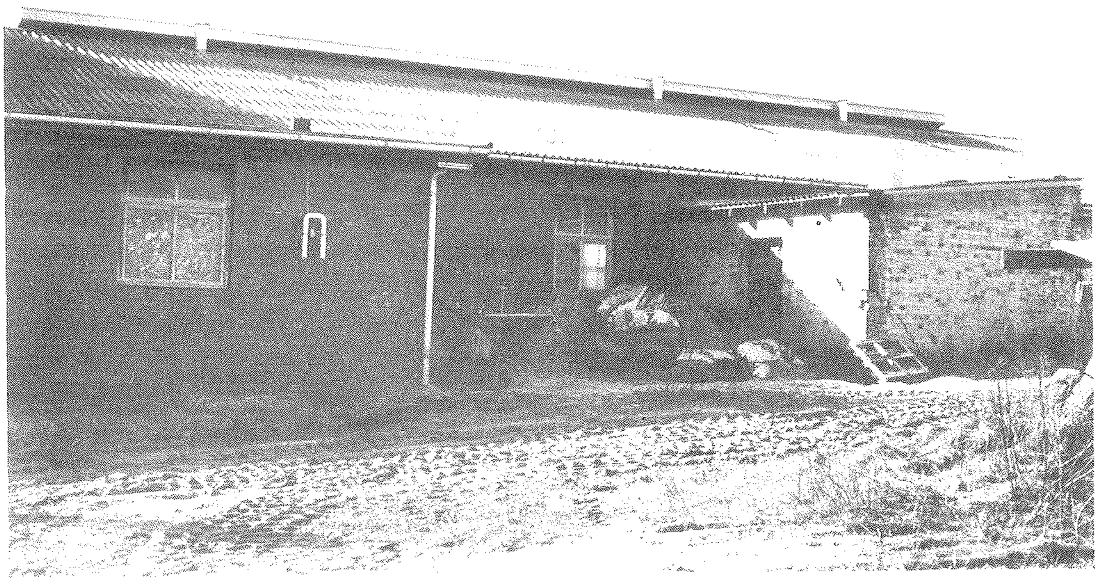

Figure 2.37. The ducts of the three bypasses for cooling the MF-panel during summertime.

2.2.3. The Controls of the System

It was decided to use a rather simple control for the system as the use of the building did not require a very precise and sophisticated control of the heating system.

The system is thus controlled by a system of interconnected thermostats and hygrostats from Danfoss. In the attic two thermostats are located, both sensing the temperature in the top of the MF-panel - figure 2.38. One of these thermostats determines if the temperature of the MF-panel is high enough to deliver solar heated air to the building. This thermostat is connected to the thermostats in the rooms. The other thermostat in the attic senses if the temperature of the MF-panel is so high, that the bypass for cooling should be opened.

The thermostat sensing the temperature in the top of the MF-panel is connected to the thermostats in the rooms in such a way that solar heated air from the MF-panels is only led into the rooms if the temperature is high enough to be utilized and the room temperatures are below a certain limit. The inlet of solar heated air is controlled separately for the three rooms.

If, however, the humidity of the rooms becomes too high in room 1 and/or room 2, but the temperature of the MF-panel is too low to be utilized, the MF-panel will be switched to exchanger mode - for each of the two rooms separately.

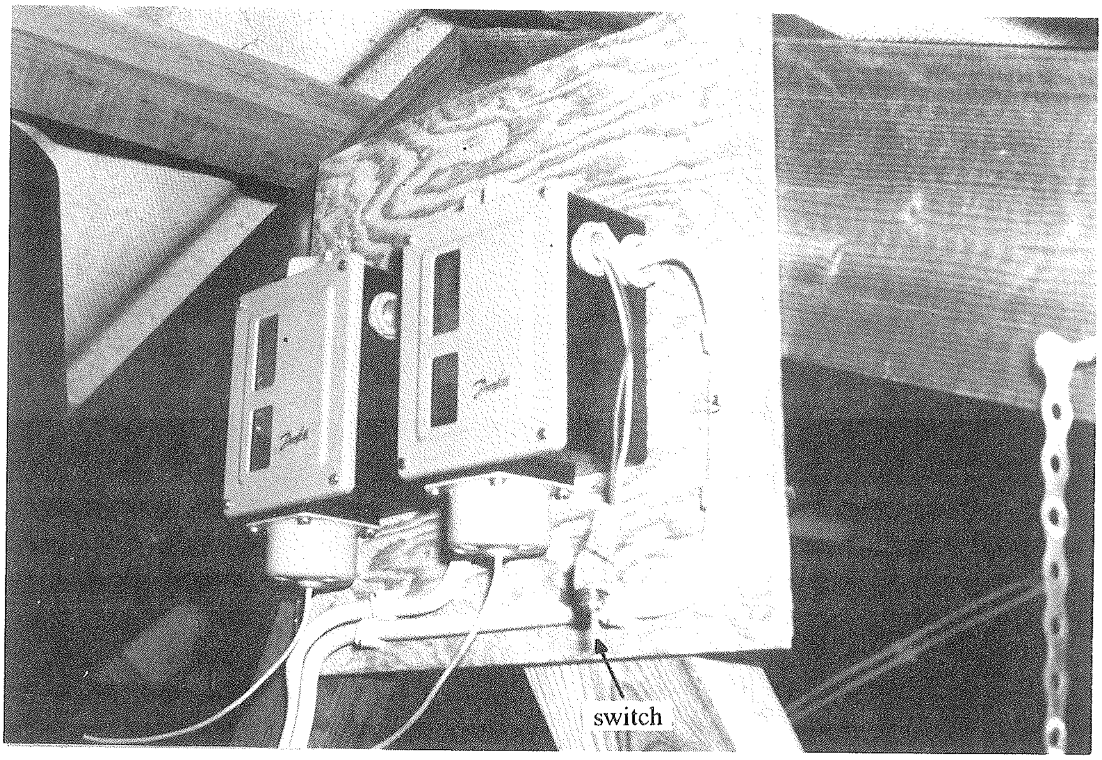

Figure 2.38. The thermostats in the attic for measuring if the temperature of the MF-panel is high enough to be utilized or so high that the bypass should be opened.

Figure 2.39 shows the thermostat and hygrostat located in room 1. The thermostat and hygrostat are located in the middle of room 1 and 2, while the thermostat of room 3 is located on the back wall under the inlet diffuser.

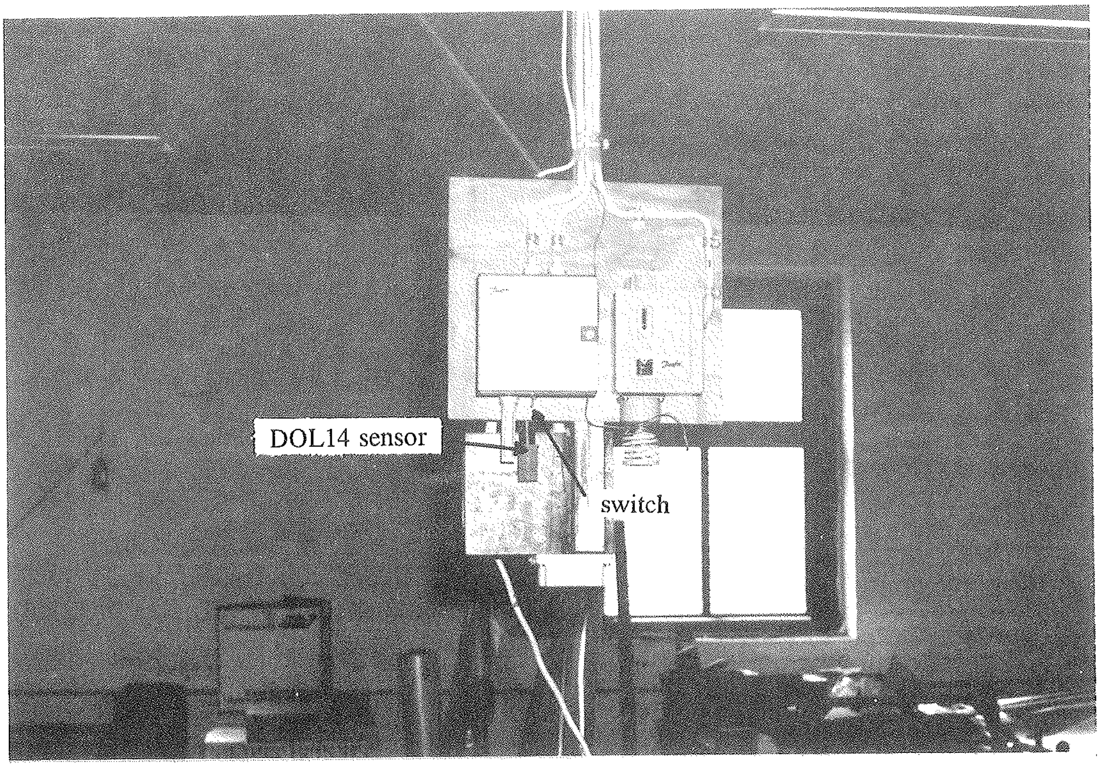

Figure 2.39. The thermostat and hygrostat of room 1.

The system was thus intended to be controlled in the following way:

> When the temperature of the MF-panel is 25°C or more and the room temperature is below 20°C, the MF-panel is started in collector mode, delivering preheated fresh air to the rooms. The fans stop when the room temperatures reach 23°C.
>
> If the temperature of the MF-panel exceeds 60°C motor dampers will open bypasses to the ambient, connected to the top of the MF-panel. In this way the maximum temperature of the MF-panel will be reduced due to natural ventilation of the panels.
>
> If the MF-panel is not in collector mode, but the humidity of room 1 and/or 2 exceeds a certain limit the MF-panel will be started in heat exchanger mode.

The above-mentioned was the intended control strategy. However, conditions and demands developed, as already mentioned, differently than expected. Due to changes in the production in the workshop it was often wished to have a rather high humidity in the rooms in order that the special-purpose bricks should not dry out too fast and thereby be damaged. The MF-system was, therefore, prevented from acting in exchanger mode. Often the inlet of solar heated air to room 1 was prevented by the workers for the same reasons - by changing the settings of the thermostat in room 1.

When this was realized it was too late to change the plans for the demonstration project. However, in order still to obtain important measurements for the system performance the controllers of the system were equipped with small switches so that the MF-panel could be forced to operate in either collector or exchanger mode during periods where it would not influence the production conditions in the workshop. The small switches are shown in figures 2.38-39 at the small arrows. This option was also utilized during the balancing and test of the system.

The speed of the fan of the system is controlled by thyristors as shown in figure 2.40. One thyristor for each room for the collector mode and 2 thyristors for each room for exchanger mode = 7 thyristors. The reason for this high number of thyristors is that the flow of the inlet air of the collector mode is different from the exchanger mode and that the flow of inlet air is different from the flow of outlet air in exchanger mode.

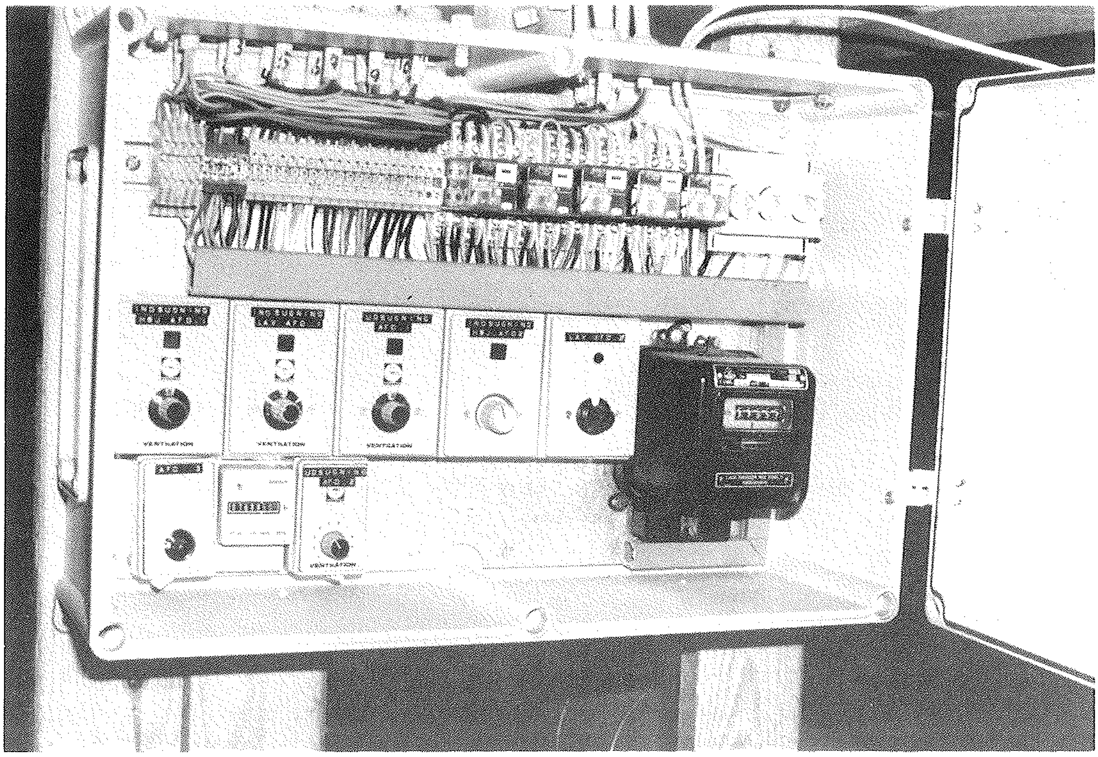

Figure 2.40. The control box in the attic containing the thyristors controlling the fans and a kWh-meter for measuring the electricity consumption of the fans - the black box. Between the two thyristors at the left bottom corner there is an hour-meter for counting the hours when the bypasses have been open.

The intention was that the air flow in collector mode should be 2 times the volume of the rooms, while the flow of fresh air in exchanger mode only should be 1 time the volume of the rooms. The flow of exhaust air in exchanger mode should be 10% higher than the flow of fresh air in order to prevent any overpressurization of the building which could force humidity into the constructions of the building.

The reason for the rather high flow during collector mode was to utilize as much as possible the solar heat and to prevent the inlet temperature from being too high and thereby uncomfortable. In reality the air flow in collector mode was approximately 2 times the volume of the building. It was approximately 28 m^3/hm^2. In exchanger mode the flow of fresh air was, however, approximately 19 m^3/hm^2 or 1.5 times the volume of the building. During exchanger mode the flow of exhaust air was only about 5% higher than the flow of fresh air. The reason for the difference between intended and real flow rates is, that it was difficult to adjust the flow rates properly, that the adjustment drifted over time and that the flow due to the viscosity of the air is temperature dependent.

2.3. The Measuring System

The heart of the measuring system is a Solartron data acquisition system connected to a portable 286 PC. The data acquisition system consists of an adaptor card in the PC and two 3-pole reed-relay voltage/current/thermocouple cards + one digital I/O card. Each of the three measuring cards has 20 gates.

The different measuring points are shown in appendix B. The following measurements are performed:

Weather:

- Solar irradiation on a plane parallel to the MF-panel
- Ambient temperature (shielded north)
- Ambient relative humidity (shielded north)

Room 1:

- Room temperature
- Relative humidity
- Temperature of the air at the four inlets
- Temperature of the air at the four outlets
- Flow of inlet and outlet of one of the four pairs of ducts
- Temperature of the air just after the flow measuring devices

Room 2:

- Room temperature
- Relative humidity
- Temperature of the air at the two inlets
- Temperature of the air at the two outlets
- Flow of inlet and outlet
- Temperature of the air just after the flow measuring devices

Room 3:

- Room temperature
- Temperature of the air at the inlet
- Flow to the room
- Temperature of the air just after the flow measuring device

MF-panel:

- Temperature of the air at four points in the outer channel
- Temperature of the air at four points in the inner channel
- Temperature of the air from the MF-panel (only in one duct)
- Temperature of the air to the MF-panel (only in one duct)
- Temperature of the air on each side of a fan

I/O card:

- Gas consumption
- Periods when the bypasses at the top of the MF-panel are open
- Control of valves in connection with the pressure transmitters for measuring the flow to room 1 and 2
- Control of the poster (not realized)

The measuring equipment for obtaining the above-mentioned measurements is described in more detail in the following.

2.3.1. The Measuring Equipment

Weather data measurements

The solar radiation on a plane parallel with the cover of the MF-panel has been measured with a Kipp & Zonen CM11 pyranometer located on the roof of the workshop to the left of the MF-panel - see figure 2.41.

The ambient temperature is measured with a copper-konstantan thermocouple type TT, while the ambient relative humidity is measured with a DOL14-sensor. The ambient temperature sensor and the DOL14 sensor are installed in a U-shaped tube shown in figure 2.42 together with a small fan. The fan is installed in the horizontal part of the tube, while the thermocouple is installed in the vertical tube to the right and the DOL14 sensor in the vertical tube to the left. The U-shaped tube is installed on the north wall of room 4. The reason for this arrangement is to have a ventilated and shielded ambient temperature sensor (ie not influenced by the solar radiation) and to protect the DOL14 against hoar-frost which will damage it.

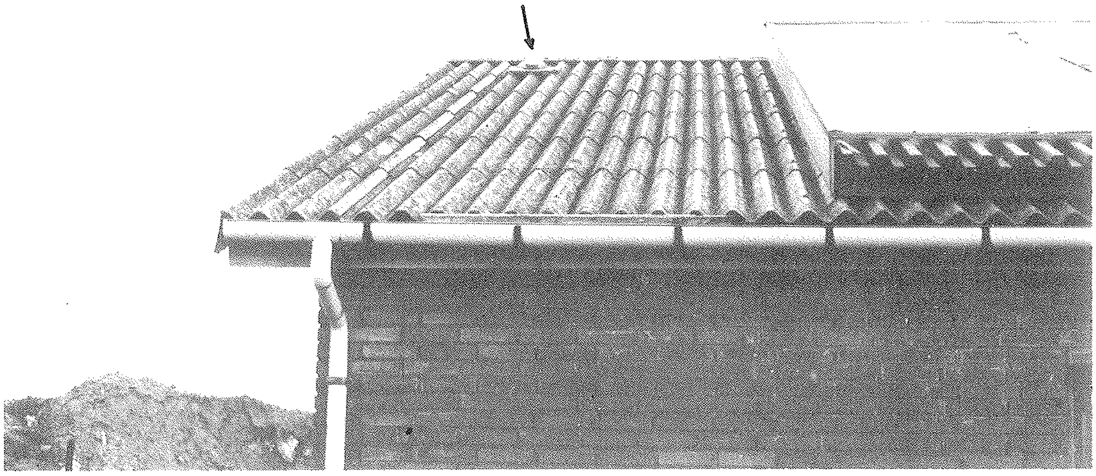

Figure 2.41. The location of the pyranometer for measuring the solar radiation on a plane parallel to the cover of the MF-panel.

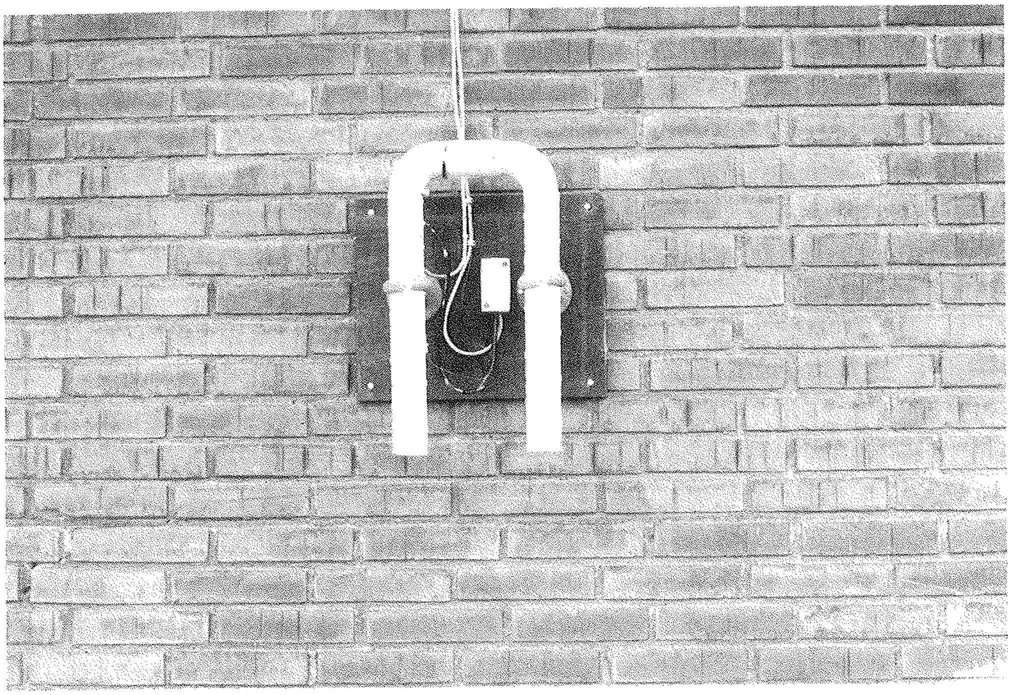

Figure 2.42. The arrangement for measuring the ambient temperature and the ambient relative humidity.

Temperature measurements in the rooms and in the system

All temperatures are measured using copper-konstantan thermocouples type TT.

The room temperature sensors are located by the room thermostats mentioned in section 2.2.3. The temperature sensors in the inlets and outlets are all located in the ducts just above the ceiling.

Special-purpose thermocouples for measuring specific temperatures have been installed in the system. Temperature sensors containing 7 thermocouples coupled in parallel have been installed in the inlet "in 3" and the outlet "out 3" of the MF-panel (figure 2.43) and on each side of the fan in the ducting of "in 3" (figure 2.44) in order to determine the amount of energy dissipated as heat from the fan to the air stream. These sensors should give a more precise reading as the 7 thermocouples are located across the cross section of the ducts as shown in figure 2.45.

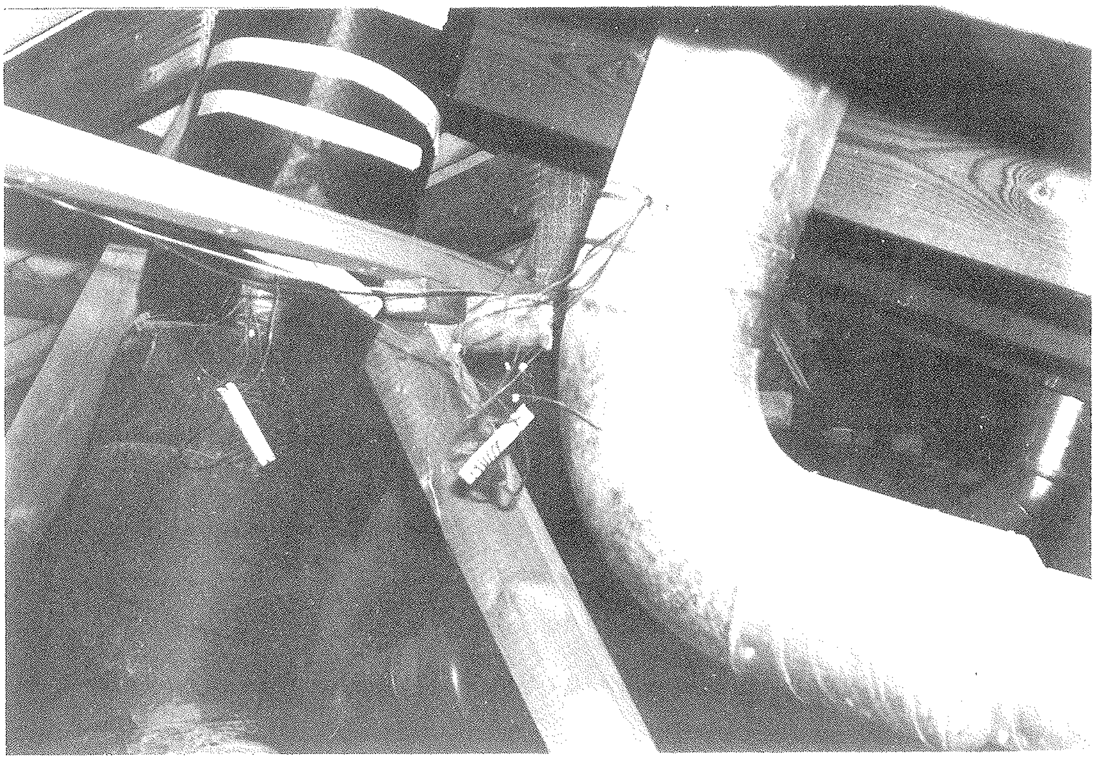

Figure 2.43. The special-purpose thermocouples at the in- and outlet of the MF-panel.

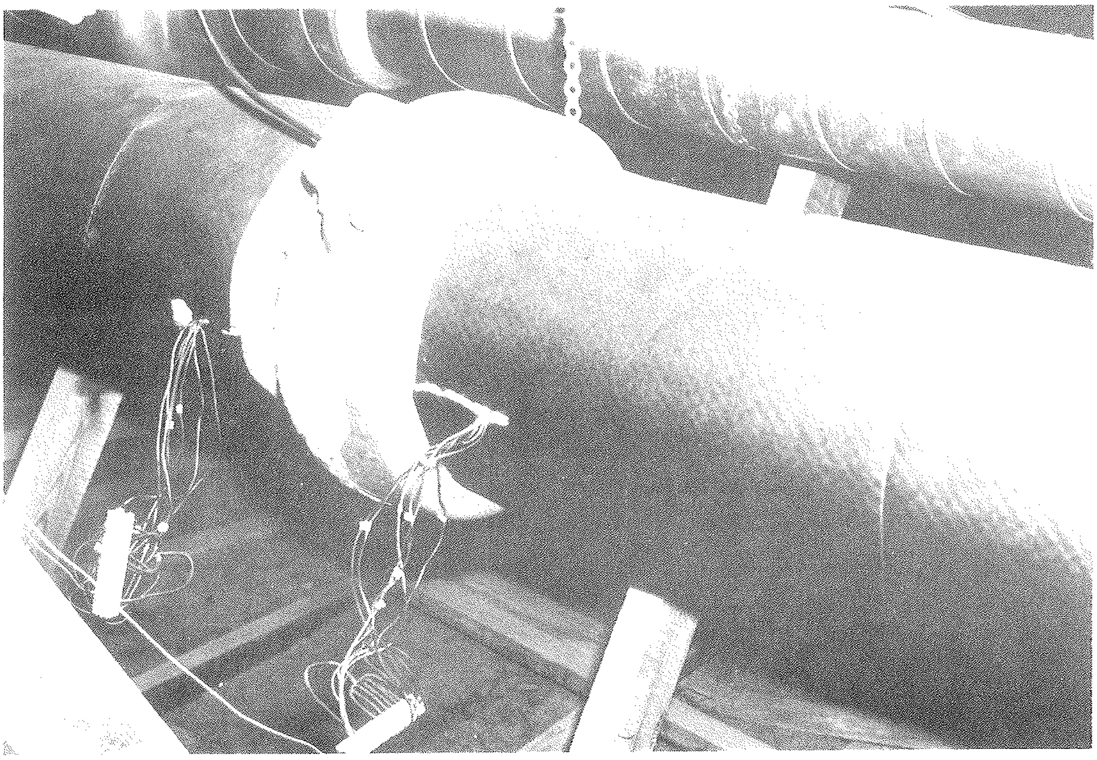

Figure 2.44. The special-purpose thermocouple on each side of a fan.

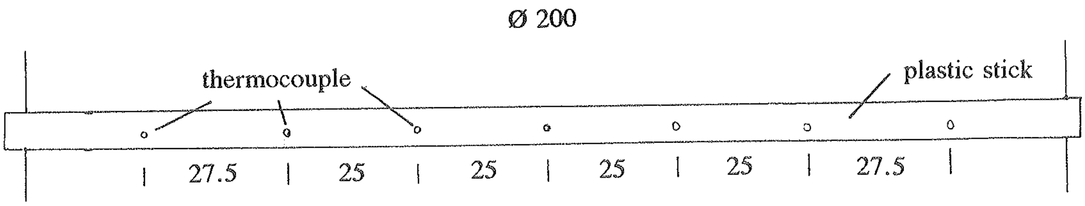

Figure 2.45. The location of the 7 thermocouples coupled in parallel in the ducts for special-purpose measurements.

8 thermocouples were located in the MF-panel - 4 under the absorber and 4 between the cover and the absorber as shown in figure 2.46. These thermocouples were located in the 13th section of the covers almost next to "in 5" and "out 5" (see figure 2.28). The intention of these thermocouples was to measure a temperature profile in the MF-panel.

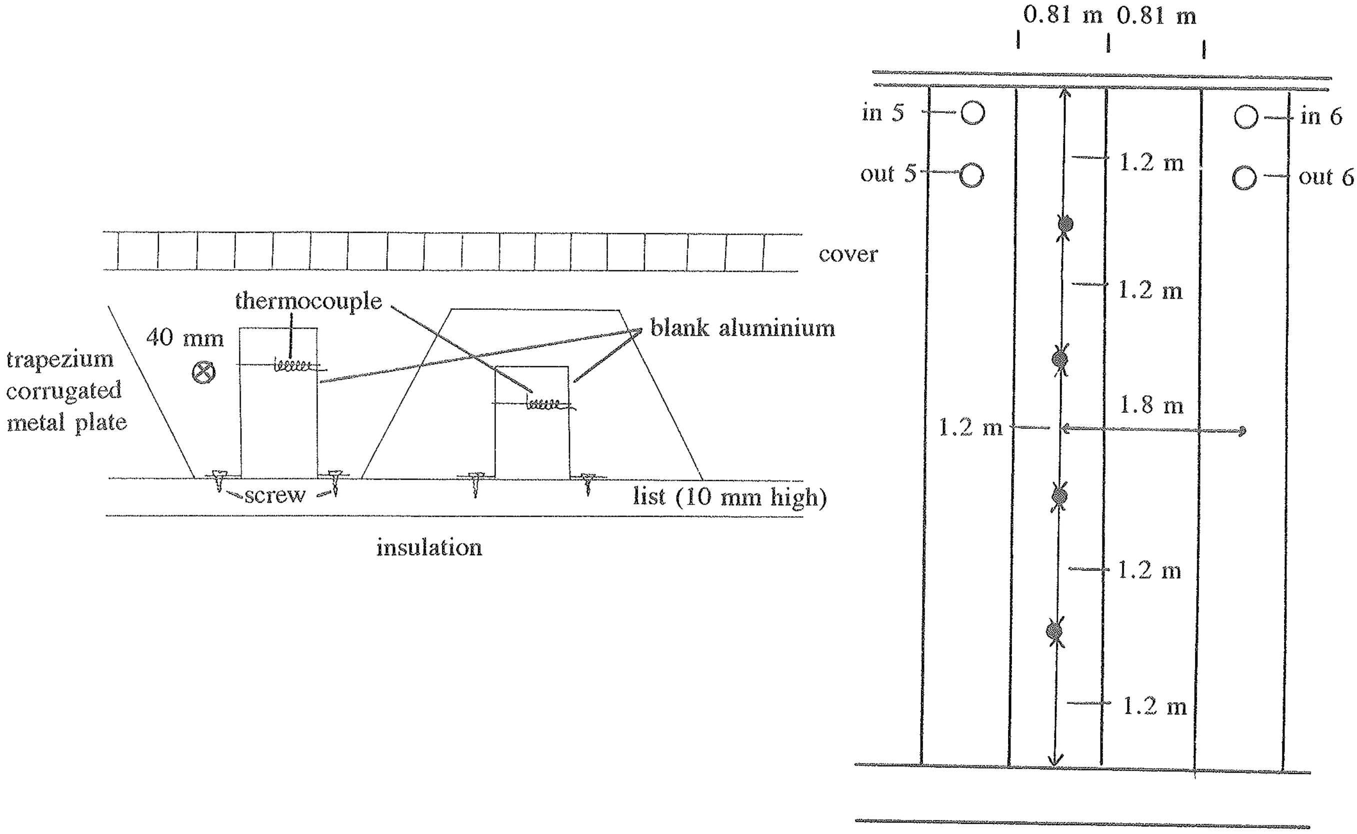

Figure 2.46. The location of the thermocouples in the MF-panel.

Flow rates

The flow rates in the system were measured by means of calibrated orifices and elbows. For room 1 and 3 the flows were measured with calibrated elbows as shown in figure 2.47, while the flows to and from room 2 were measured by means of calibrated orifices as shown in figure 2.48.

The pressure drop was measured over the calibrated orifices and elbows by means of pressure transmitters. For room 1 the pressure drop is only measured across one inlet and one outlet elbow of the eight elbows installed in this system. Based on mutual measurements for different flow rates on all 8 elbows, the equations for the two elbows have been calibrated so that the total flow rates to room 1 may be calculated based only on the measuring of the pressure drops across the two elbows.

Pressure transmitters are rather expensive, so an arrangement where two flow measuring devices share one pressure transmitter has, therefore, been utilized, as shown in figure 2.49. The pressure drop is measured over one orifice, then the valves are operated by means of the data acquisition system and half a minute later the pressure drop is measured across the other orifice.

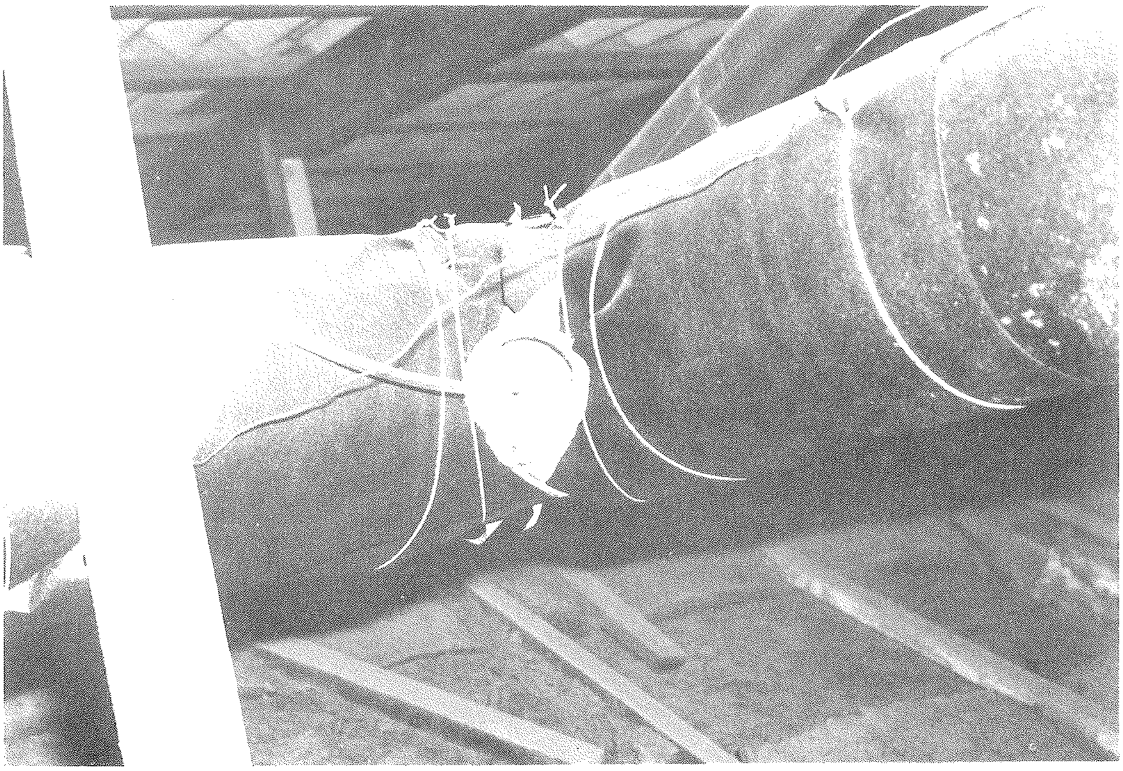

Figure 2.47. The calibrated elbow used for measuring the flows to and from room 1 and 3.

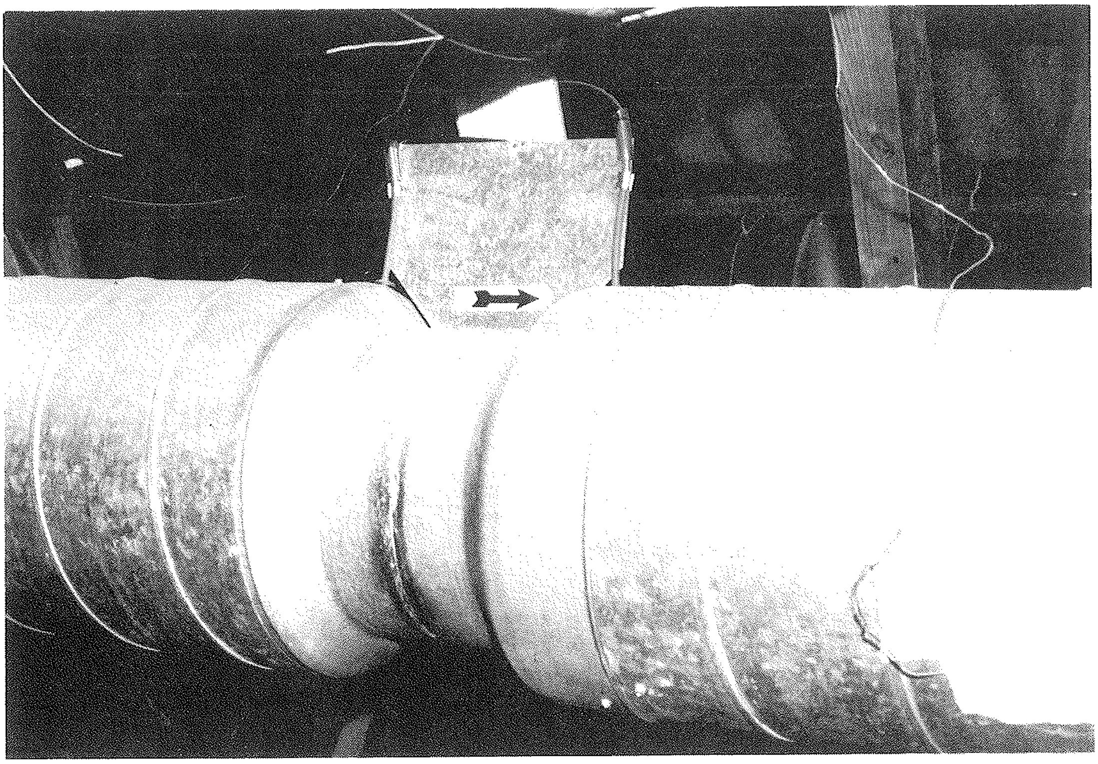

Figure 2.48. The calibrated orifice used for measuring the flows to and from room 2.

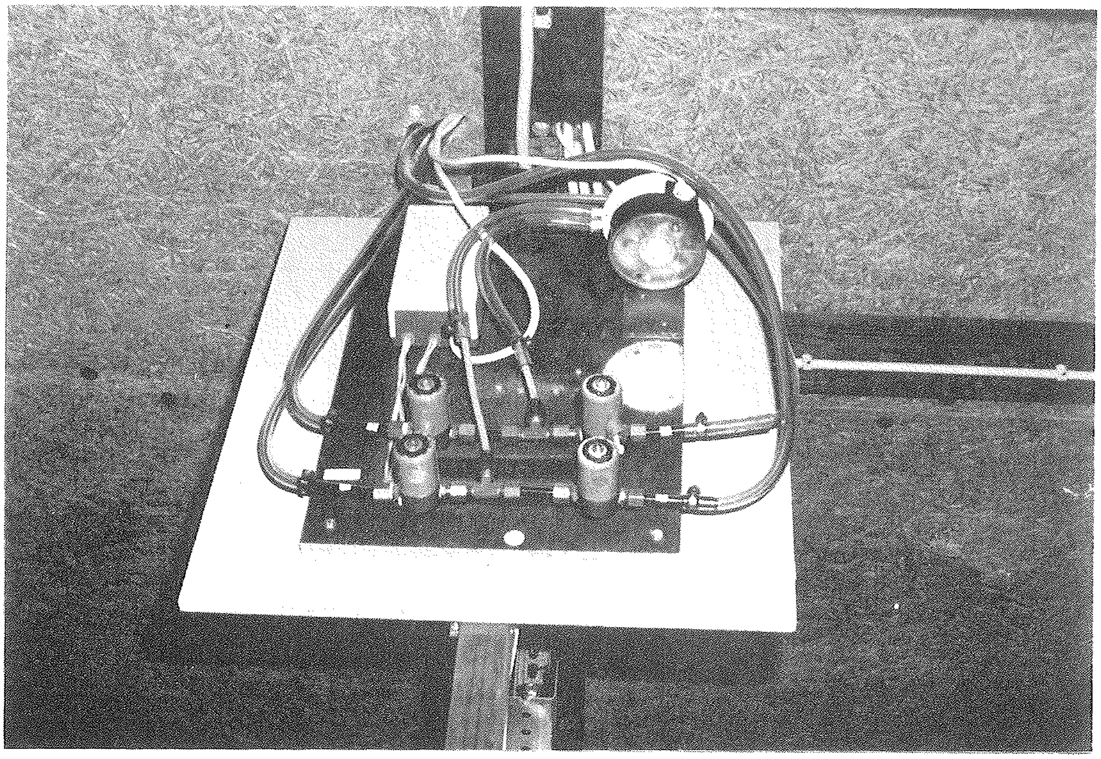

Figure 2.49. The valve arrangement where two orifices may share one pressure transmitter. The pressure transmitter is located in the top right corner of the arrangement.

The originally used pressure transmitters were from Furness Controls. They are very precise but have a tendency to drift especially when they are exposed to large temperature swings. The two valve arrangements with pressure transmitters were from the beginning located in the attic over room 1 beside the two 3-pole reed-relay voltage/current/thermocouple cards. However, the very high temperature in the attic during summer-time made the pressure transmitters totally unreliable. The valve arrangements with the pressure transmitters were, therefore, moved down to room 1. In order to protect the pressure transmitters and in order to decrease the noise from the valves, naturally ventilated boxes of insulation foam were made and put in front of the valve arrangements as seen in figure 2.50.

However, it was not possible to ensure a proper function of the pressure transmitter for measuring the flow rates to room 1. This pressure transmitter was, therefore, replaced with a pressure transmitter from Staefa as seen in figure 2.49.

Figure 2.50. The box for protection of the pressure transmitter for measuring the air flows to room 2. The box is located just under the ceiling on the wall separating room 1 and 2. The photograph also shows the opening to the attic.

Relative humidity

The relative humidity in room 1 and 2 was measured by means of DOL14 sensors located beside the sensor of the hygrostats - see figure 2.39.

According to the manufacturer's information the uncertainty on the DOL14 sensors was ±2% of maximum reading. However, comparison with a calibrated handheld sensor showed differences between this sensor and the DOL14 sensors of up to 25%. Calibration factors were, therefore, introduced in the measuring program to account for this. It was, however, not possible to decrease the difference between the handheld sensor and the DOL14 sensors to less than 10% (for the maximum difference).

The idea with the DOL14 sensors was to investigate how much the MF-panel as heat exchanger would reduce the relative humidity in the building. But as the MF-panel was not allowed to operate in this mode, the measurements from the DOL14 sensors were of minor importance, so the effort to calibrate these sensors was stopped.

Hour counters

In order to measure the periods with open bypasses and the gas consumption of the boiler, the motor damper of the bypasses and the burner of the boiler were connected to hour counters. In order to obtain a measure for the gas consumption the readings of the hour counter of the burner was compared with reading of the official gas meter of the building.

2.3.2. The Data Acquisition System

As already mentioned, the data acquisition system consisted of 3 measuring cards from Solartron connected to a PC. The PC was located in a cupboard in room 4 together with the digital I/O card as seen in figure 2.51, while the two 3-pole reed-relay voltage/current/thermocouple cards were located in the attic over room 1 as seen in figure 2.52.

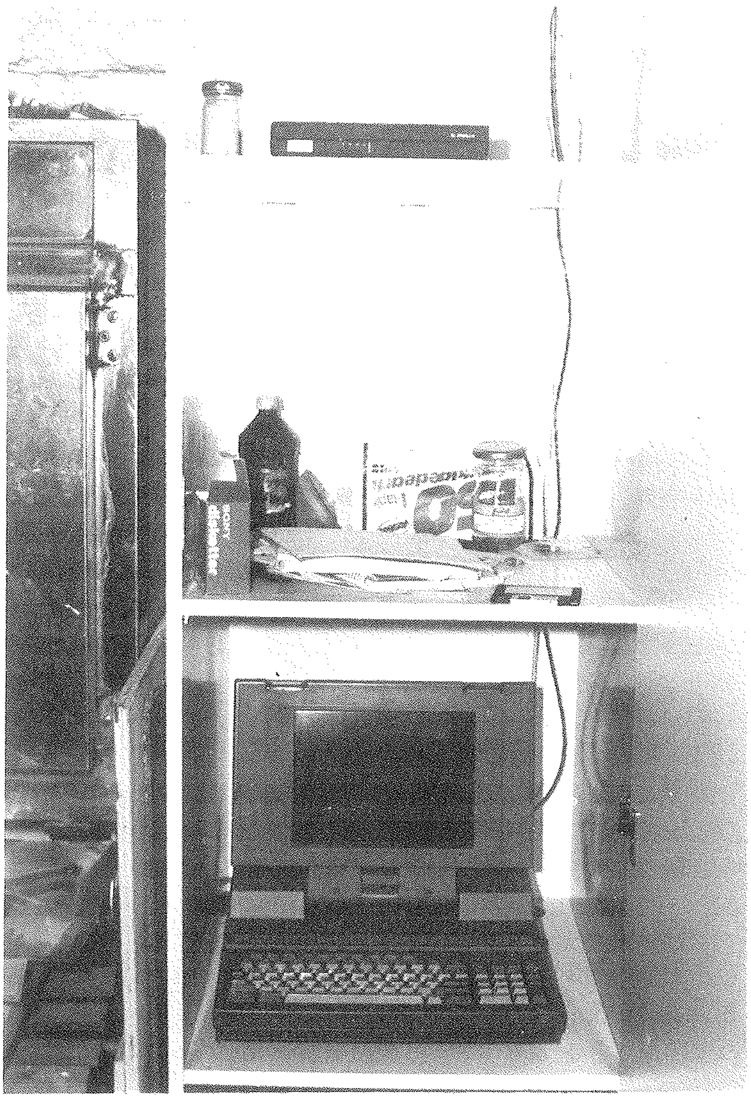

Figure 2.51. The cupboard with the PC of the data acquisition system. The digital I/O card was located on the top shelf.

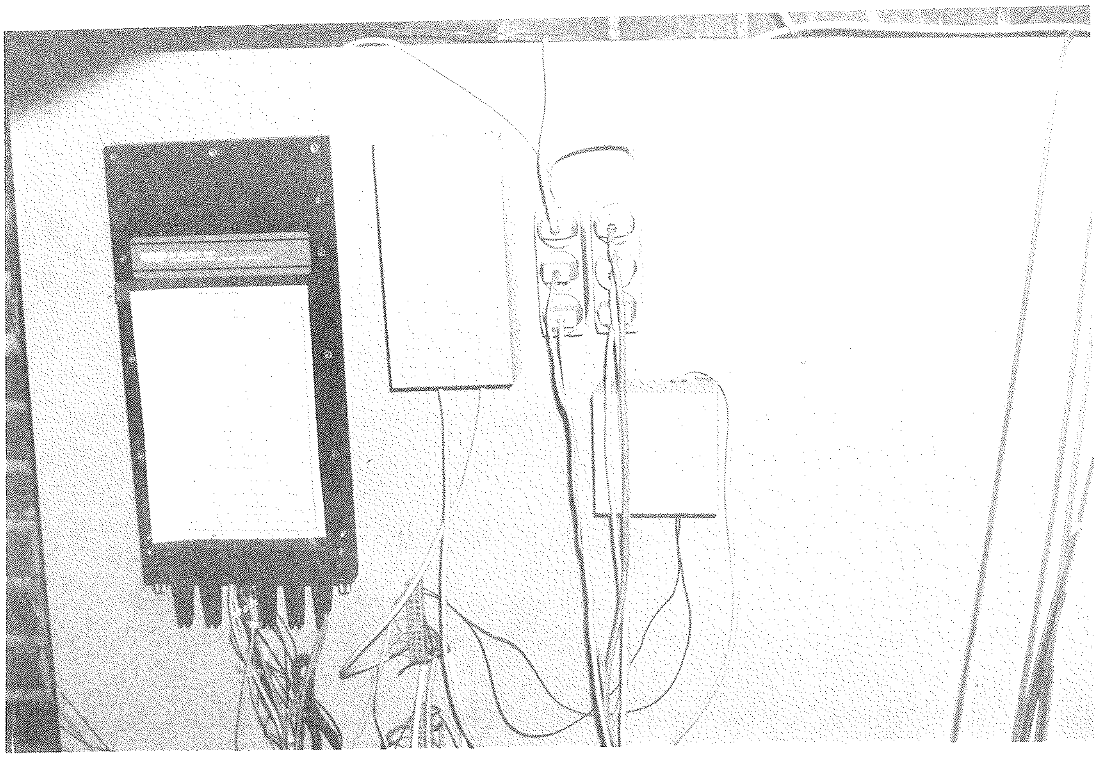

Figure 2.52. One of the 3-pole reed-relay voltage/current/thermocouple cards located in the attic over room 1. The two boxes to the right are the power supply for the DOL14 sensors and the fan in the U-shaped tube for measuring the ambient temperature and the ambient relative humidity. One of the valve arrangements and pressure transmitters was originally located in the free space to the right - but was moved down to room 1.

The measuring cards were controlled by the PC through a special-purpose software developed by the Thermal Insulation Laboratory especially for this project. Commercial software was tried, but could not meet the requirements of the project.

The measuring cards were triggered and data was obtained every minute. Based on the measured data, flows, energy fluxes, efficiencies, etc were calculated for the system. The measured and calculated values were averaged (as floating mean values) in 30-minute mean values and stored on floppy disks. Version 8 of the measuring program for the PC can be found in appendix C.

The measurements were carried out automatically by the PC. There were, however, also implemented facilities for performing manually controlled measurements via the keyboard of the PC. In this way it was possible to inspect single measuring points, if something was wrong in the system.

On the screen several important system parameters were shown and minutely updated. These parameters were:

- Solar irradiation
- Ambient temperature
- Ambient relative humidity
- The three room temperatures
- The relative humidity of room 1 and 2
- The flow to the rooms
- The flow from room 1 and 2
- The mean temperature of the air to the rooms
- The mean temperature of the air from room 1 and 2
- The energy supplied to the rooms
- The energy extracted from room 1 and 2
- The efficiency of the heat exchanger/solar collector
- The consumption of gas and related energy consumption
- An indication of, whether the bypasses are open or closed
- 8 temperatures in the MF-panel

The displayed system parameters were mainly used to obtain a quick impression of whether the system and the measuring system were operating as supposed.

The two 3-pole reed-relay voltage/current/thermocouple cards were used for measuring the temperatures, the pressure drops across the pressure transmitters (voltage output), the voltage of the pyranometer and the voltage of the DOL14 sensors.

The digital I/O card was used to read the hour counters (pulses). This card should also have been used to control diodes in a poster showing the actual operation of the system. The measuring program of the PC has an implemented feature for this purpose. Based on the measured values from the system the measuring program determines the operation of the system. The I/O card is then triggered in such a way that diodes in a schematic drawing of the system would show the air flows. This feature of the data acquisition was, however, unfortunately not utilized.

The measuring data has as already mentioned been stored on disks in 30-minute mean values. More than 60 measured and calculated values describing the system performance were stored every 30 minutes. Each day has been stored in separate files which were opened and closed every 30 minutes. This was done in order not to lose data in case of breakdown of the PC. All measured and calculated values have been stored on disk in order not to lose information if, for some reason, the calculated values were infected with errors.

3. Performance of the System

The building was as already mentioned not ideal for the demonstration of the MF-panel system, and changes in the production within the workshop during the installation of the MF-panel system made it even less applicable for this demonstration. The measuring system and the MF-panel system were, therefore, changed in such a way that it was possible to perform special-purpose experiments with the system during periods when it would not disturb the production in the workshop or create any discomfort for the workers. Based on measurements from the normal operation of the system and on measurements from special-purpose measurements it is possible to extrapolate to other buildings.

The present section first describes the results from the measurements - both from normal operation and from special-purpose experiments. At the end of the section, based on the measurements, the performance is extrapolated to a more ideal building.

3.1. Results from the Measurements

The system and the measuring system were started in November 1991. The start-up of the system and especially the start-up of the measuring system successively exposed errors both in the system and in the measuring system; the latter included both hardware and software errors. These errors were corrected and the first real measurements started March 18, 1992. The registration of the hour counters was, however, first started on June 26, 1992. The measuring was stopped on June 24, 1994. More than 2 years of measurements have thus been obtained. The measuring system has been running without serious problems. There are, however, some holes in the measurements - mainly due to problems with the PC.

Except for smaller holes in the measured data - typically half an hour to a few hours - major holes are to be found in the following periods:

1992	August	26, 13:00 - 27, 8:30
	November	10, 20:30 - December 4, 10:30
1993	August	20, 9:00 - 30, 10:30
	November	23, 16:30 - rest of the year
1994	January	1, 0:00 - 21, 10:30
	April	25, 11:30 - 25, 23:00

For the hole in November 1992 the measuring program of the PC did for some unexplained reason begin to write illegal characters into the data files on the disk. This stopped when the program was stopped and restarted.

The hole in August 1993 was due to a too late replacement of the disk.

The hole from November 23, 1993 to January 21, 1994 was due to a breakdown in the power supply of the PC. The error was difficult to locate and correct.

Special-purpose software for treating the measured data and extract/calculate key-values for the system has been developed and applied on the data sets.

3.1.1. Yearly Performance

The yearly performance of the MF-system installed in this particular building is analyzed in this section.

The workers did, as already mentioned, switch of the inlet of solar heated air to room 1 during several periods. The system of room 1 was thus completely switched of during July -November (maybe also December) 1993. For this reason only the year from June 1992 - May 1993 (both months inclusive) is investigated in this section. For months with holes in the measurements it is assumed that the obtained measurements are representative for these months.

Figures 3.1-2 show the weather conditions (mean monthly ambient temperature and integrated solar irradiation on a plane parallel to the cover of the MF-panel) for the above-mentioned year compared with the weather conditions for the Danish Test Reference year - TRY (Statens Byggeforskningsinstitut, 1982).

The figures show that the actual weather during the above-mentioned period has been warmer and more sunny than the TRY. The measured mean temperature was 0.8°C higher than the annual ambient temperature of the TRY, while the measured solar irradiation on a plane parallel with the cover of the MF-panel was 5% higher than for the TRY.

For the heating season October-April (both months inclusive) the measured mean ambient temperature was 0.7°C higher than for the TRY, and the solar irradiation was 3.5% higher than for the TRY.

The gas consumption during the measured year - June 1992 - April 1993 - equals 164,000 kWh, while it during the heating season was 143,350 kWh. There was a small heat demand during the summer for raising the morning temperature of the rooms to a comfortable level and in order to decrease the drying time of the brick beams. In this section only the heat demand during the heating season is considered, as it is not normal for Danish buildings to have a space heating demand outside the heating season, and because the actual space heating demand occurred early in the morning, often before the MF-panel was able to deliver the heat. The heat from the MF-panel resulted thus often, in this period, in an increase of the room temperature to a higher level than required, and can as such hardly be labelled a gain.

It is difficult to determine the savings due to the installation of the MF-panel. The following definition has been used: The energy demand of the building for space heating is the actual gas consumption of the boiler + the energy supply from the MF-panel defined as the energy in the inlet air - calculated based on the room temperature and the inlet temperature - divided with the efficiency of the gas boiler. The efficiency of the gas boiler was measured to be 0.93.

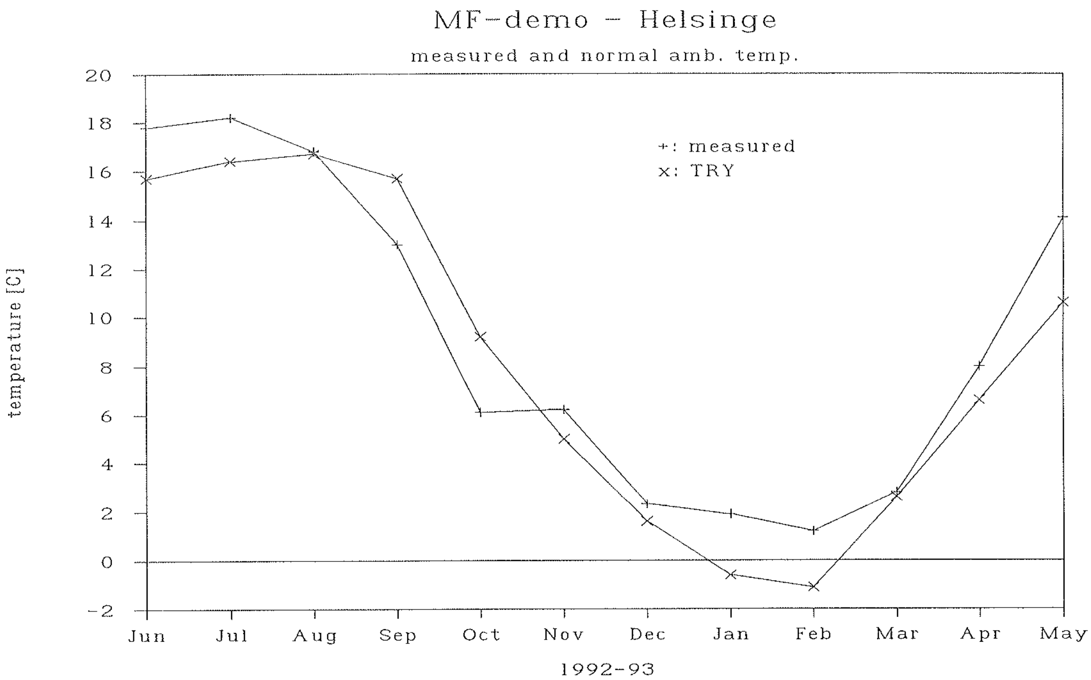

Figure 3.1. The measured mean monthly ambient temperature versus the mean monthly ambient temperature for the Danish Test Reference Year.

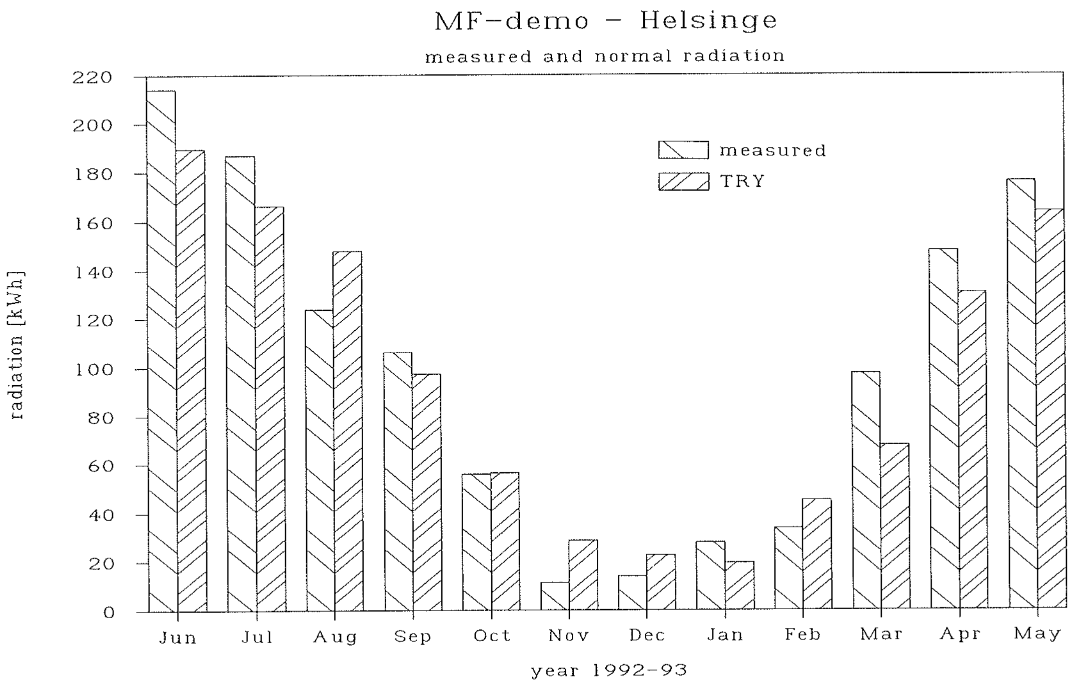

Figure 3.2. The measured integrated monthly solar irradiation on a plane parallel with the cover of the MF-panel versus the integrated monthly solar irradiation from the Danish Test Reference Year on the same plane.

The energy actually delivered to the building from the MF-panel may be defined in two different ways: If it is pestimistically assumed that the ventilation through the MF-panel system is excess ventilation so that the system only participates in covering the space heating demand at inlet temperatures higher than the room temperature, the energy delivered from the MF-panel is only the part of the energy in the inlet air calculated based on the room temperature and the actual inlet temperature. However, if it is assumed, that the air from the MF-panel replaces a proportional part of the heat loss due to natural infiltration, then the energy delivered in the inlet air may be calculated based on the ambient temperature and the actual inlet temperature.

The latter definition of the delivered amount of energy from the MF-panel gives the largest gain. It may be justified to use this definition as the MF-panel creates a small overpressure in the building decreasing the amount of natural infiltration. However, the reality is most probably to be found somewhere in between. Both definitions are, therefore, used in the following.

The energy supply from the MF-panel during the heating season has been measured to be 7,080 and 12,130 kWh using the two above-described definitions. This gives a solar fraction of 5.5 and 7% respectively. Figure 3.3 shows the solar fraction month by month for the heating season using the two definitions for the energy delivered from the MF-panel.

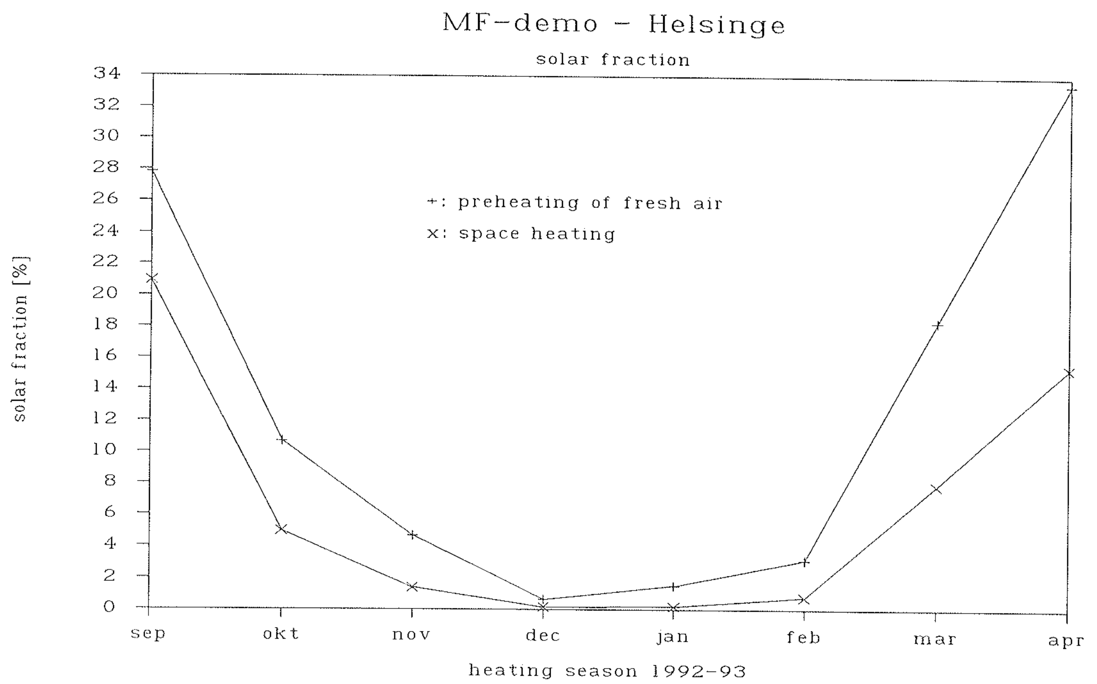

Figure 3.3. The measured solar fraction of the MF-panel for the heating season October 1992 - April 1993 (both months inclusive) using the two definitions for the energy delivered from the MF-panel.

During the year investigated here the solar irradiation and the ambient temperature have been higher than for the Test Reference Year. However, the system of room 1 has during the investigated period been switched off during smaller or longer periods. This has of course decreased the performance of the system. Based on a more detailed inspection of the measured data it is judged, that the performance of the MF-panel system would have been approximately 5% higher, if the system of room 1 had not been switched off. This more than compensates for the increased performance due to better weather conditions.

The amount of energy delivered from the MF-panel is much lower than foreseen in appendix A. This is of course due to the fact, that the MF-panel did not act as heat exchanger between the fresh air to the building and exhaust air from the building as the amount of saved energy for this mode of operation is much larger than for the collector mode. In appendix A is furthermore assumed that fresh air to the building is always let through the MF-panel, while the actual MF-panel only preheats the air if the outlet temperature of the MF-panel is higher than the room temperatures.

The annual performance for the two definitions of the energy supply from the MF-panel system equals 56 and 96 kWh/m². This is very much lower than the expected performance described in the introduction. However, considering the very difficult operating conditions the MF-panel system has been exposed to, the performance is acceptable. It is the building and the operation which have not been acceptable. The performance of the MF-panel system installed in a more ideal building will be estimated later in this section.

The performance of the MF-panel system will in the following be investigated in more detail. First detailed measurements from two weeks will be discussed; after that the efficiencies of the collector and the heat exchanger will be calculated and discussed. The operation of the bypasses for cooling the MF-panel during summer-time will furthermore be evaluated.

3.1.2. Detailed Performance

In the following some results from a two-week period in 1992, March 19 - April 1, Julian days 79-93, are shown.

Figure 3.4 shows the solar irradiation on the MF-panel and the ambient temperature during the considered period.

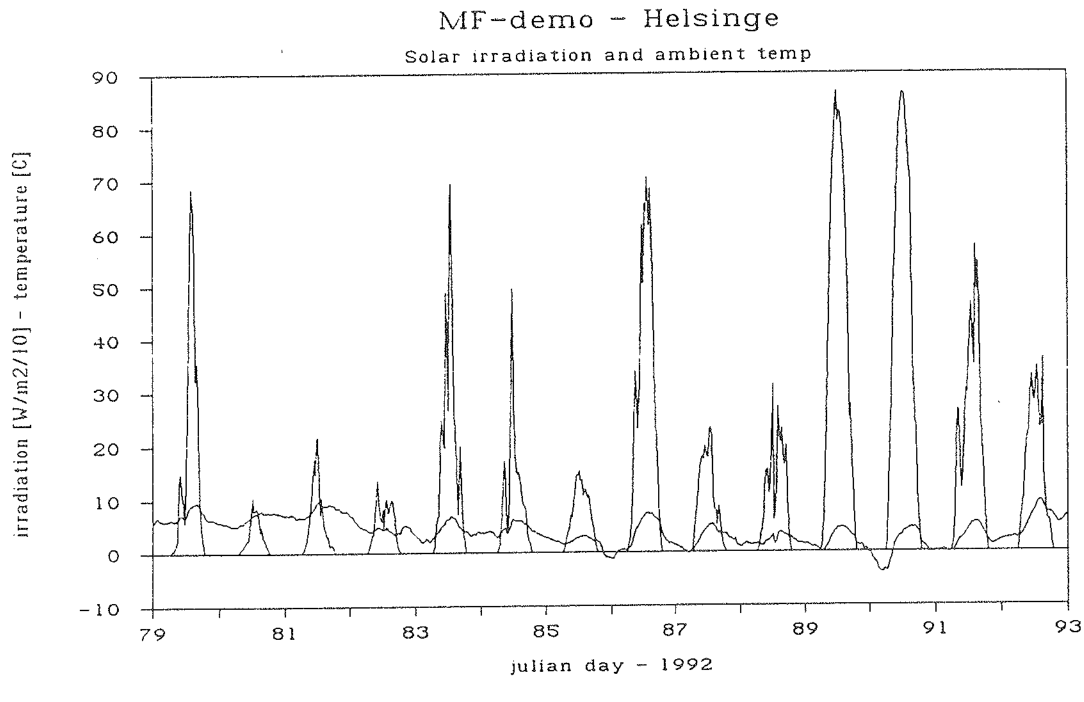

Figure 3.4. Solar irradiation on the MF-panel and the ambient temperature.

Figure 3.5 shows the four temperatures in the collector part of the MF-panel. The thermocouples are located in the outer channel between the cover and the corrugated metal sheet (see figure 2.46), the first one 1.2 m from the bottom, and then 1.2 m between the thermocouples so that the upper thermocouple is located 1.2 m from the top. Figure 3.6 shows the same as figure 3.5, but only for the last four days of the period. It can be seen that the temperature of the incoming air is increased considerably - up to more than 50°C (figures 3.5-6).

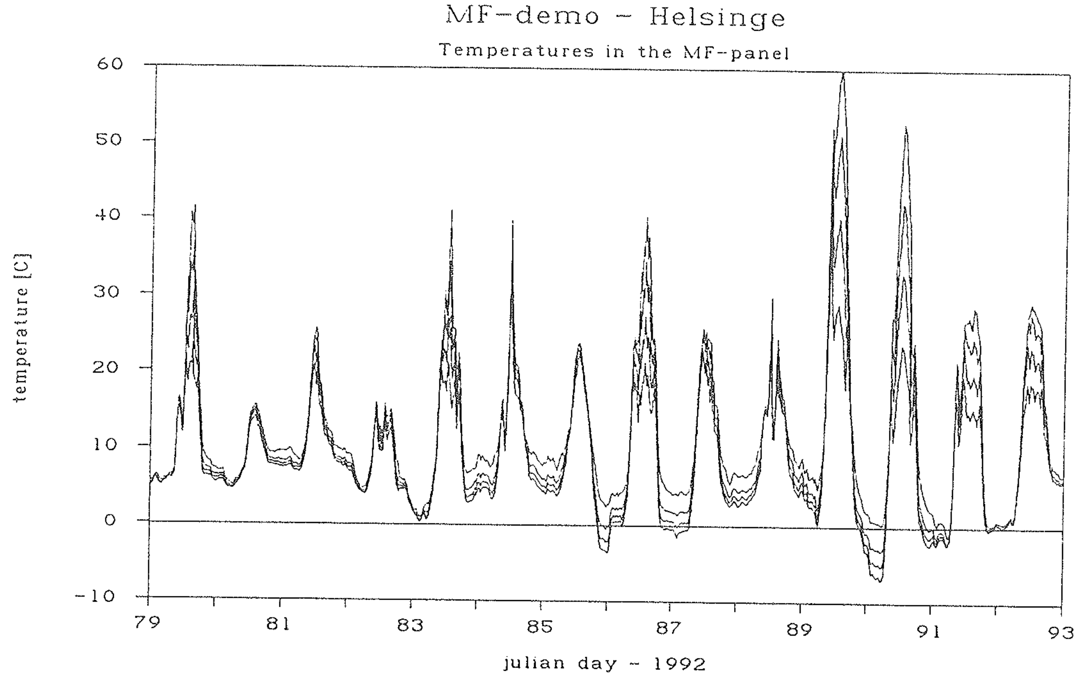

Figure 3.5. Four temperatures in the collector part of the MF-panel.

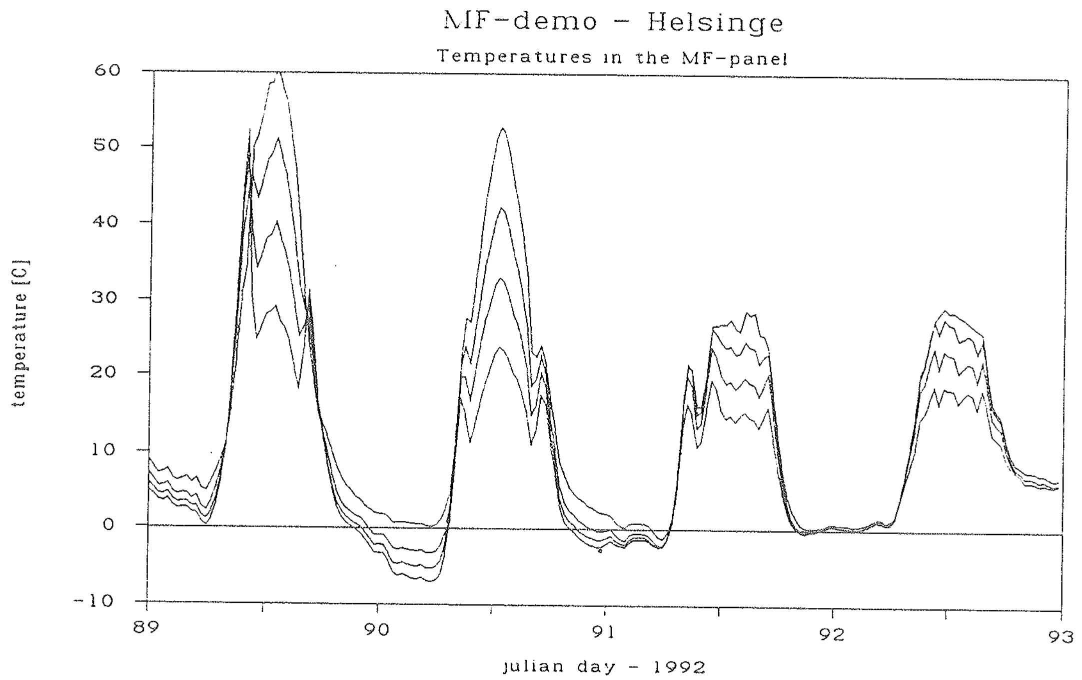

Figure 3.6. The last four days of figure 3.5.

Figures 3.7-9 show the room temperature in the three rooms. The temperature of the incoming air is also shown, but only for periods where air actually is blown into the rooms. It can be seen, that the preheated air increases the temperature of the rooms by 4-6°C.

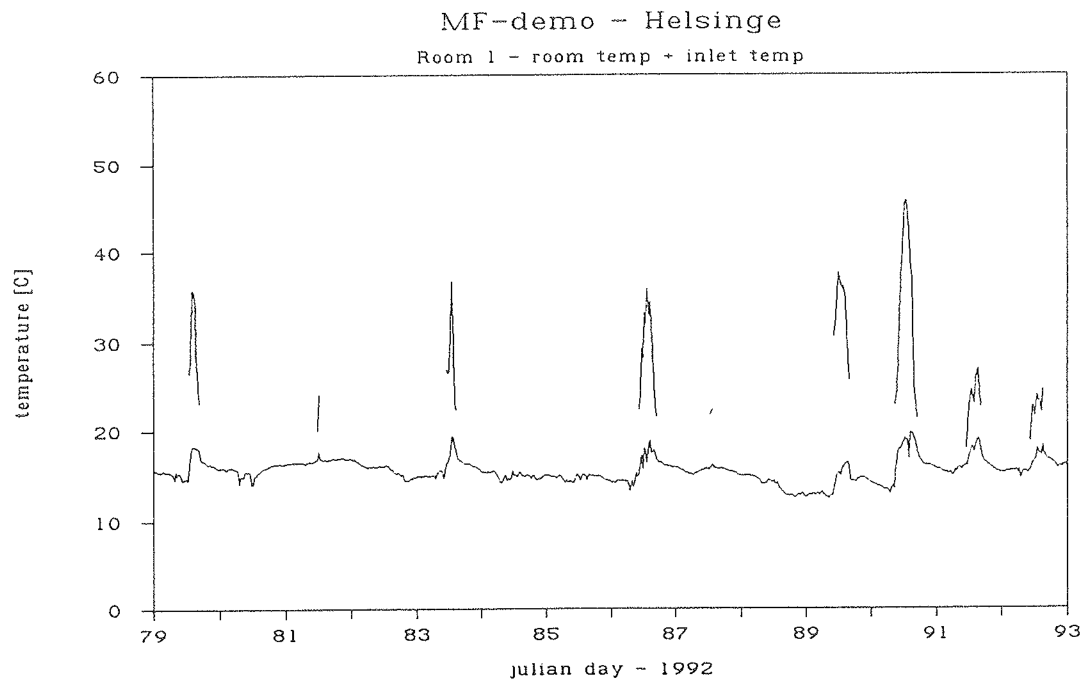

Figure 3.7. Room temperature of room 1 + the temperature of the incoming air stream for the periods with flow.

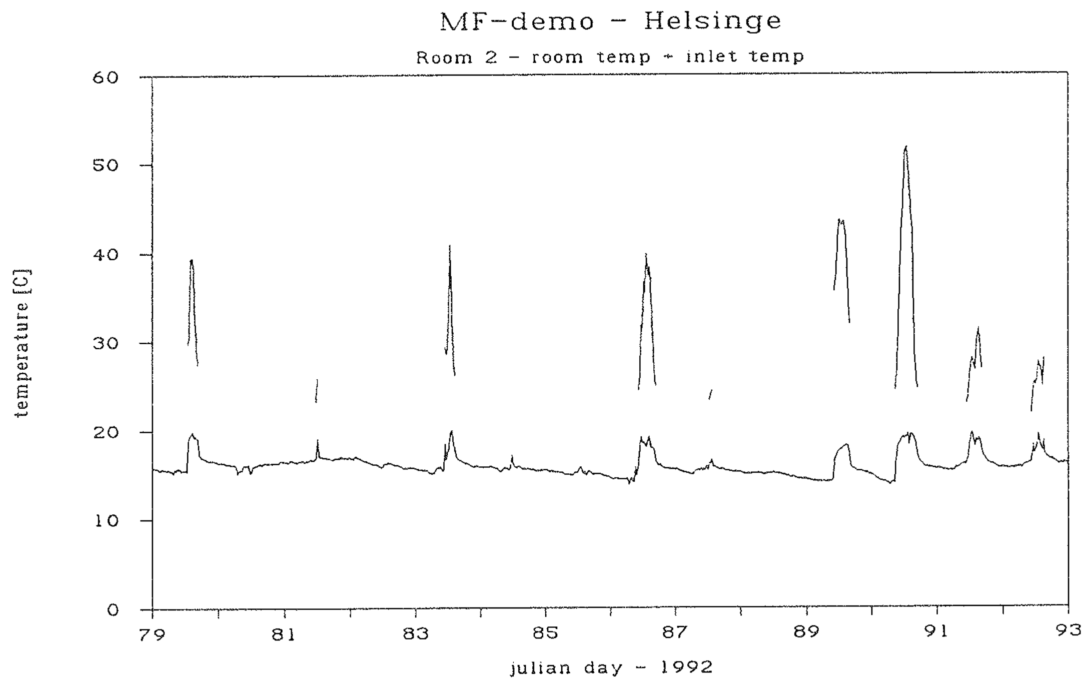

Figure 3.8. Room temperature of room 2 + the temperature of the incoming air stream for the periods with flow.

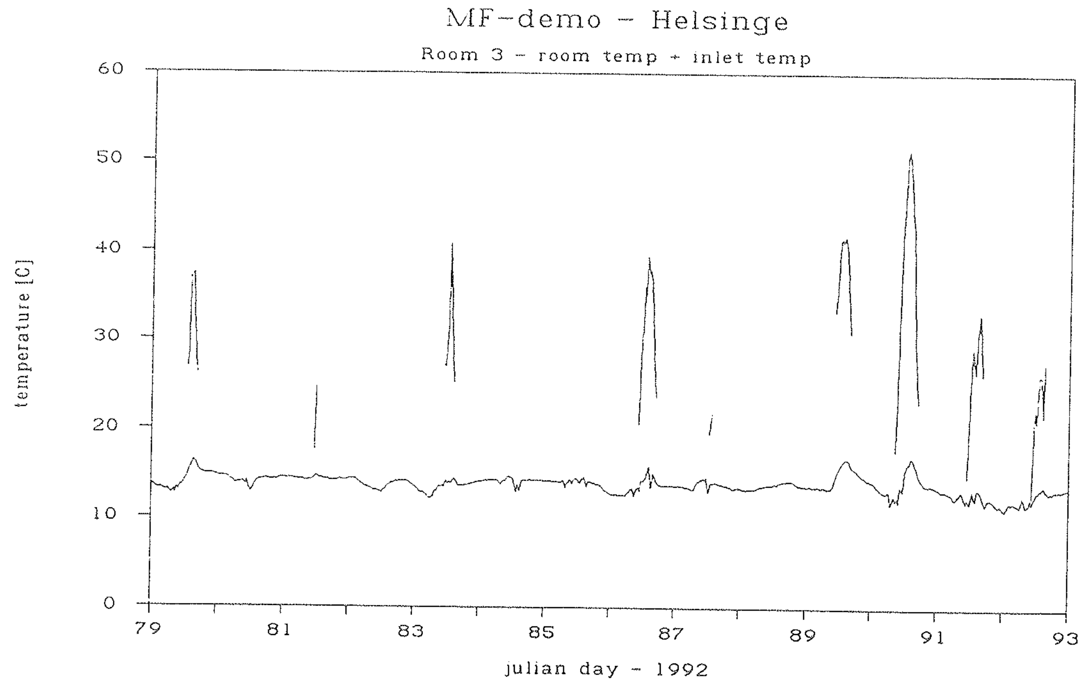

Figure 3.9. Room temperature of room 3 + the temperature of the incoming air stream for the periods with flow.

Figures 3.10-12 show the energy supplied to the room during the period. The total energy supply was measured to 533 kWh. The gas boiler has during the same period used 1035 m^3.

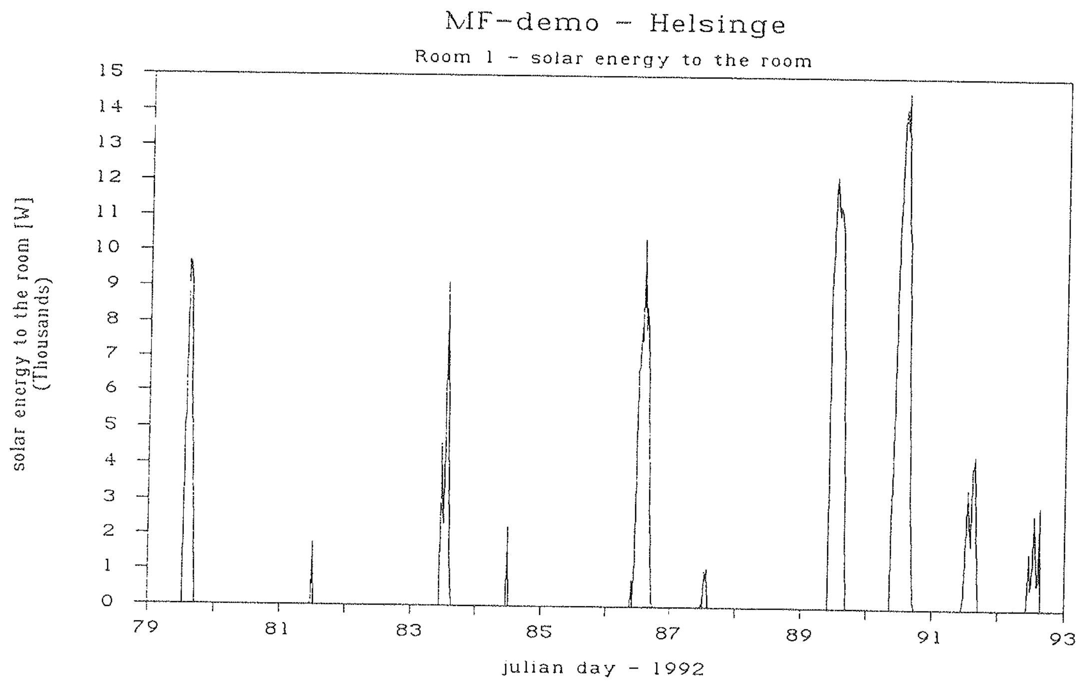

Figure 3.10. The energy supply from the MF-panel to room 1.

Figures 3.7-9 show the room temperature in the three rooms. The temperature of the incoming air is also shown, but only for periods where air actually is blown into the rooms. It can be seen, that the preheated air increases the temperature of the rooms by 4-6°C.

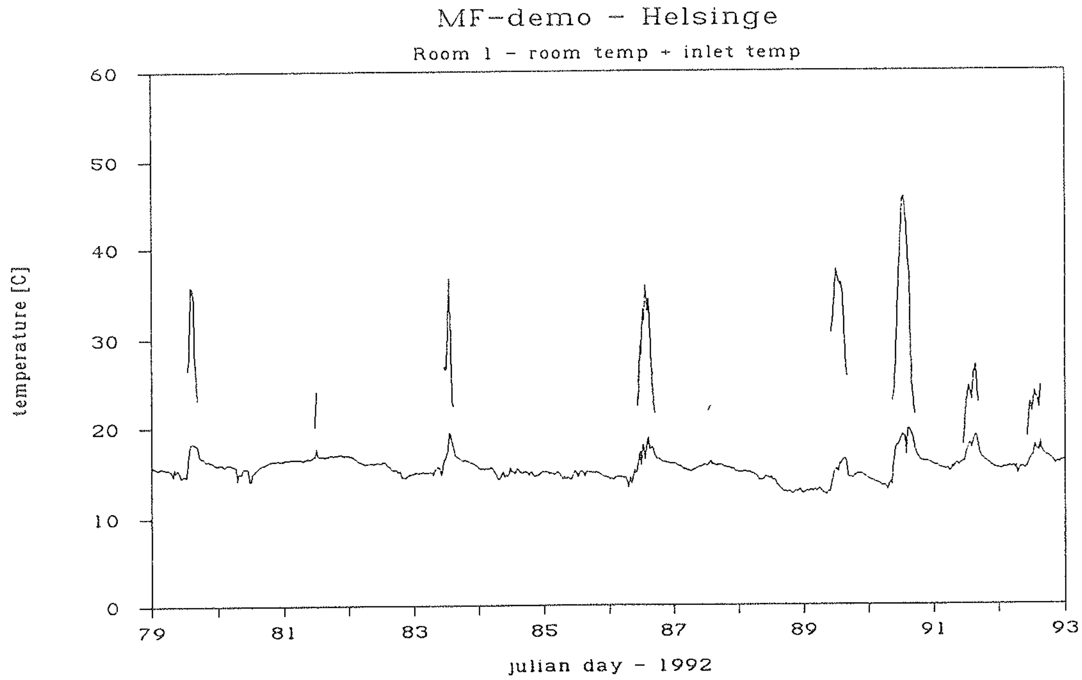

Figure 3.7. Room temperature of room 1 + the temperature of the incoming air stream for the periods with flow.

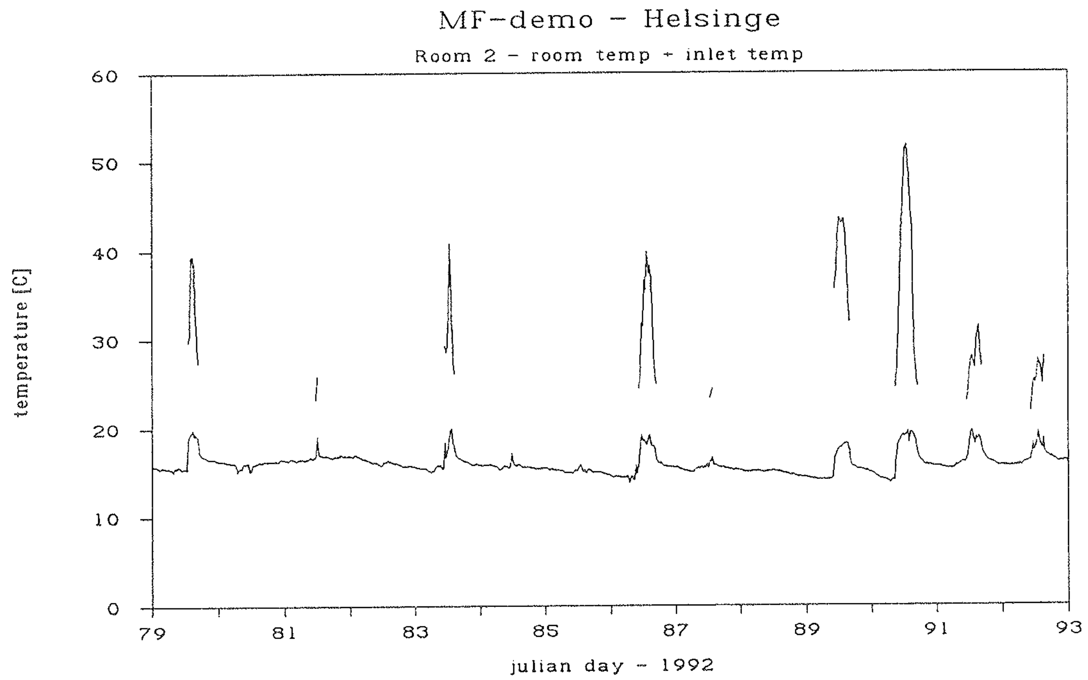

Figure 3.8. Room temperature of room 2 + the temperature of the incoming air stream for the periods with flow.

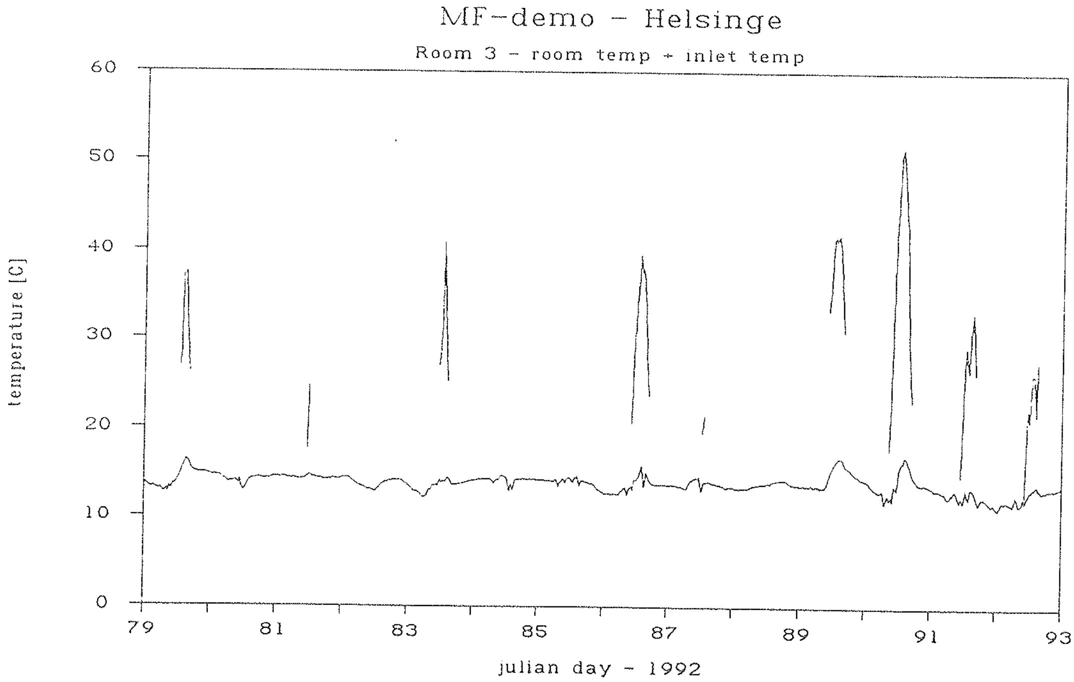

Figure 3.9. Room temperature of room 3 + the temperature of the incoming air stream for the periods with flow.

Figures 3.10-12 show the energy supplied to the room during the period. The total energy supply was measured to 533 kWh. The gas boiler has during the same period used 1035 m^3.

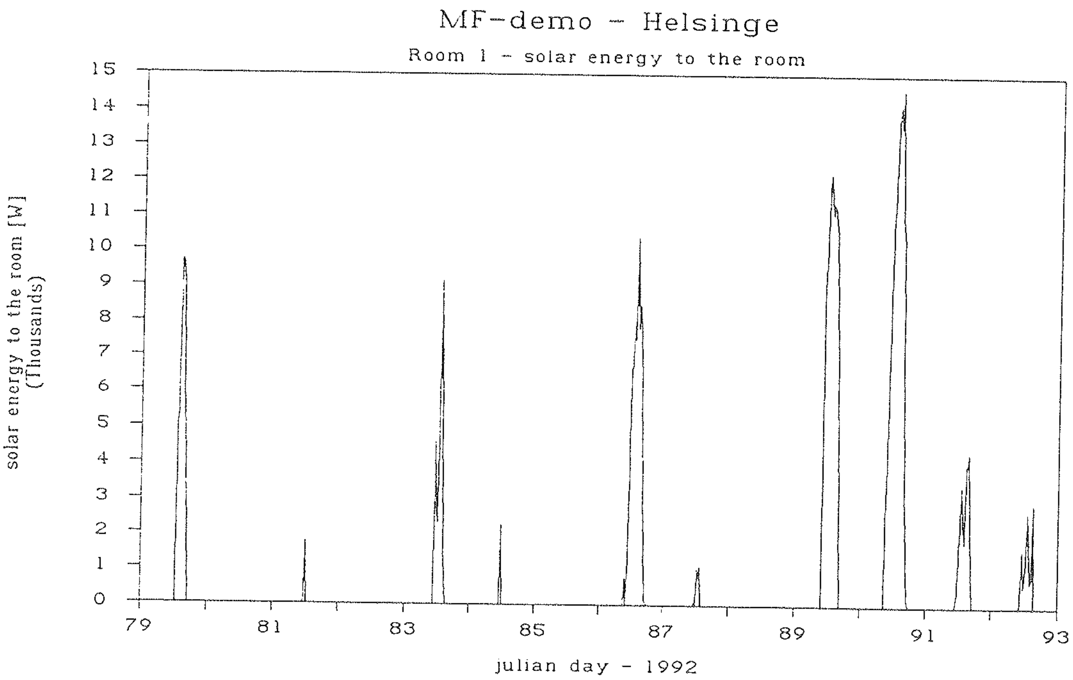

Figure 3.10. The energy supply from the MF-panel to room 1.

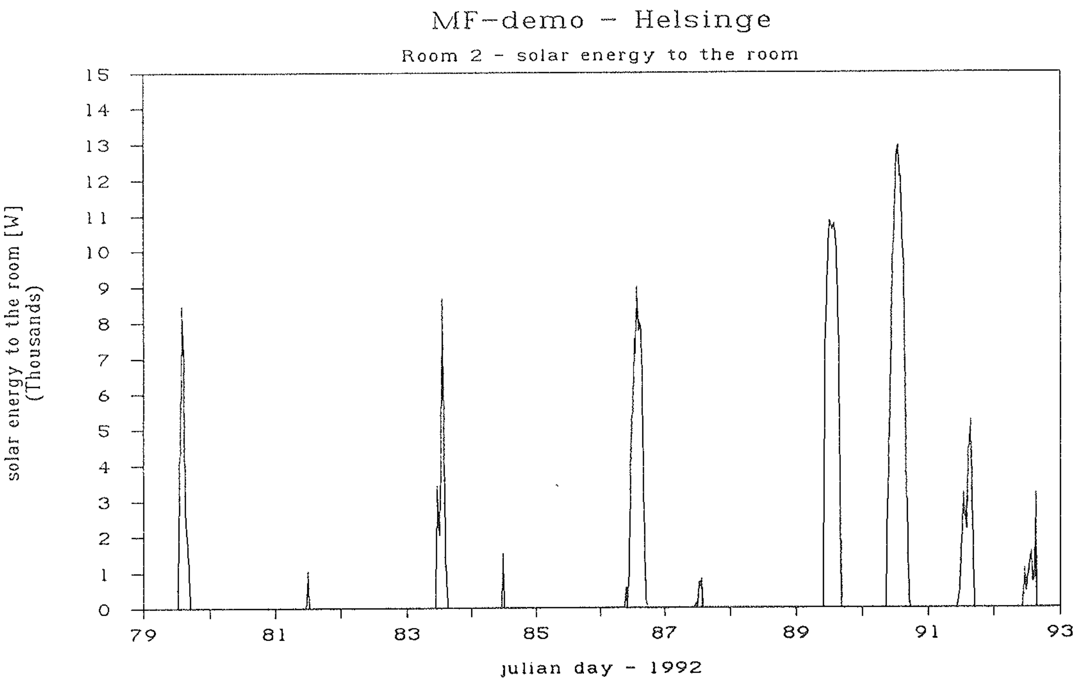

Figure 3.11. The energy supply from the MF-panel to room 2.

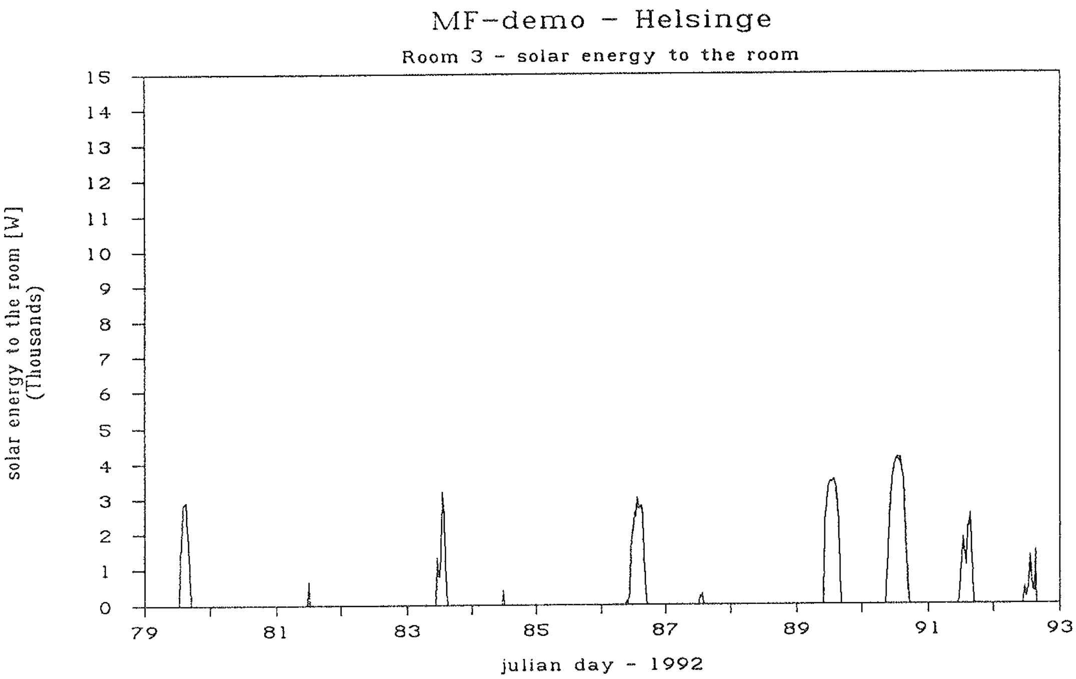

Figure 3.12. The energy supply from the MF-panel to room 3.

The efficiency of the boiler is measured to be 93% and the total heat demand of the building is assumed to be equal to the energy delivered from the boiler + the energy from the MF-panel. The MF-panel has then delivered 4.8% of the energy demand. The reason for this relatively low contribution from the MF-system is, as already mentioned, that the system has not been operating in the heat exchanger mode.

The air flow through the MF-panel was approximately 28 m^3/m^2h. The efficiency of the MF-panel should, therefore, according to figure 1.3 have been about 32%, but the measured efficiency was between 35-40%. The MF-panel seems, therefore, to be more efficient than expected. This is further investigated in the following section.

3.1.3. The Efficiency of the MF-panel as Solar Collector

The efficiency of the MF-panel operating purely as a solar collector is investigated in this section. The efficiency of the MF-panel acting as solar collector is defined as the energy delivered to the rooms (calculated on basis of the ambient temperature and the inlet temperature to the rooms) divided by the solar radiation on the MF-panel.

The efficiency shown in figure 1.3 has been measured under steady state conditions with an incidence angle of the radiation of zero and a radiation of approximately 900 W/m^2. It is of course not possible to obtain such stable conditions under real weather conditions, but the following conditions will result in almost the same conditions as used for obtaining the efficiencies shown in 1.3: Only values where the radiation is above 600 W/m^2 and the incidence angle is below 30° are considered. The demand of a radiation above 600 W/m^2 means that periods with much diffuse radiation is excluded. Incidence angles of ±30° from zero have almost no effect on the transmission of the radiation through the cover. This later demand is fulfilled when only considering measurements obtained between 10:00 and 14:00. The measurements are averaged into half-hourly mean values with the storage time as the label, so only measurements with the labels 10:30, 11:00, 11:30, 12:00, 12:30, 13:00, 13:30 and 14:00 are considered in this investigation. Furthermore, only periods when solar heated air has been delivered to all three rooms have been considered.

A special-purpose program was developed for finding the measurements which fulfil the above-mentioned criteria, to calculate the efficiencies of the 3 arrays and of the total MF-panel and write them to a file for further treatment. When using the program it was shown that only very few measurements fulfilled the criteria in the period September-December. So in order to make the presentation of the results more clear only measurements from the spring will be treated here.

The following results are obtained from: March-May, 1992, March-June, 1993 and February-June, 1994. 342 measured values passed the above-mentioned criteria.

The following figures 3.13-17 show the efficiency of the MF-panel acting as a solar collector. The calculation of the efficiency has both been carried out on the 3 arrays separately and on the whole MF-panel. An array is here defined as the part of the MF-panel connected to eg room 1. The calculation of the efficiency in figures 3.13 and 3.15-17 is based on the energy supplied to the rooms calculated from the ambient temperature and the inlet temperature to the rooms. This, however, results in a somewhat smaller efficiency as a heat loss occurs in the ducts between the MF-panel and the rooms. The efficiency of array 1 is, therefore, also calculated based on the ambient temperature and the temperature out of the MF-panel obtained using the special-purpose temperature sensor located in the outlet from the MF-panel as described in section 2.3 and shown in figures 2.43 and 2.45. This efficiency is shown in figure 3.14.

The efficiencies are shown depending on the Julian day. Results from all three years are shown on the graphs.

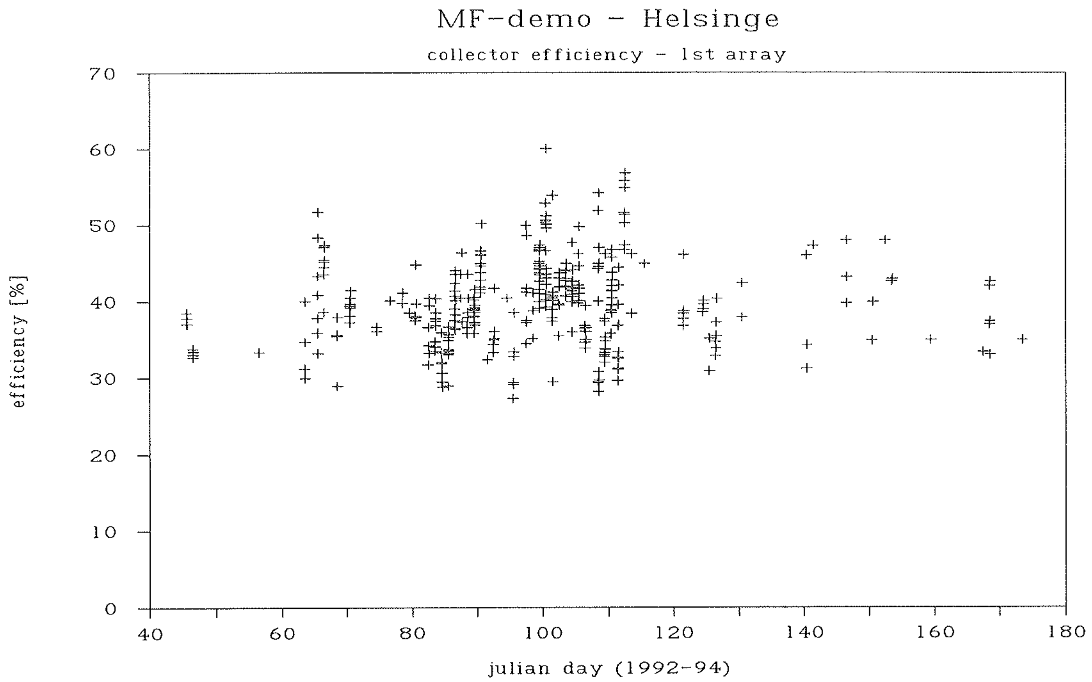

Figure 3.13. The efficiency of the first array of the MF-panel acting as solar collector. The first array supplies preheated air to room 1.

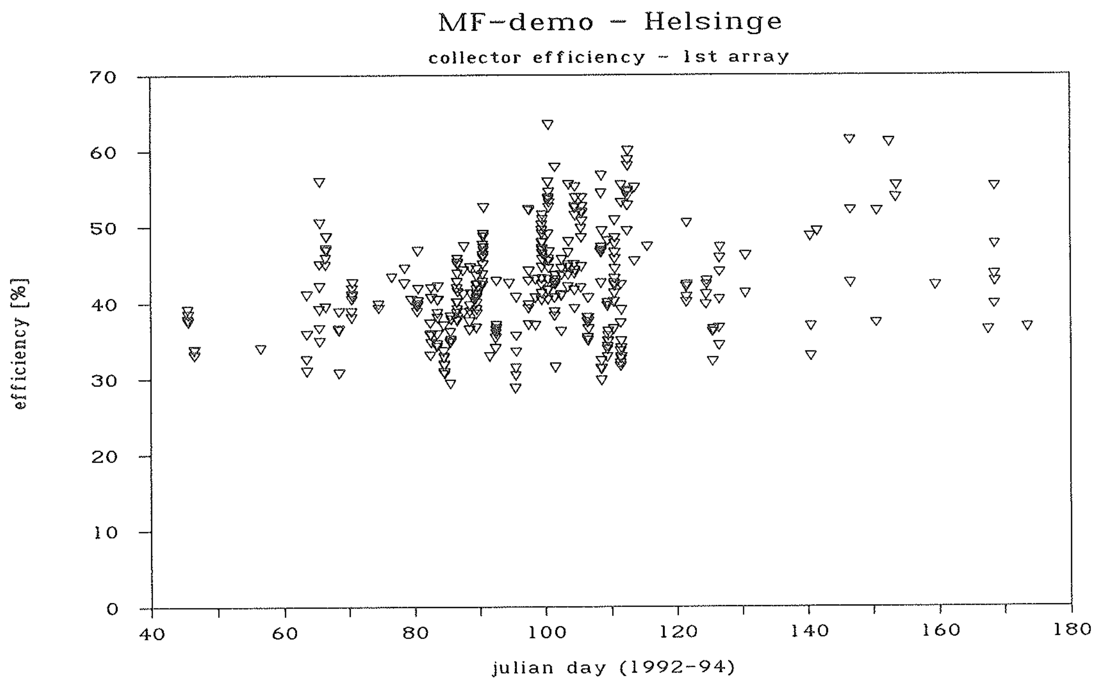

Figure 3.14. The efficiency of the first array of the MF-panel acting as solar collector, based on the outlet temperature from the MF-panel. The first array supplies preheated air to room 1.

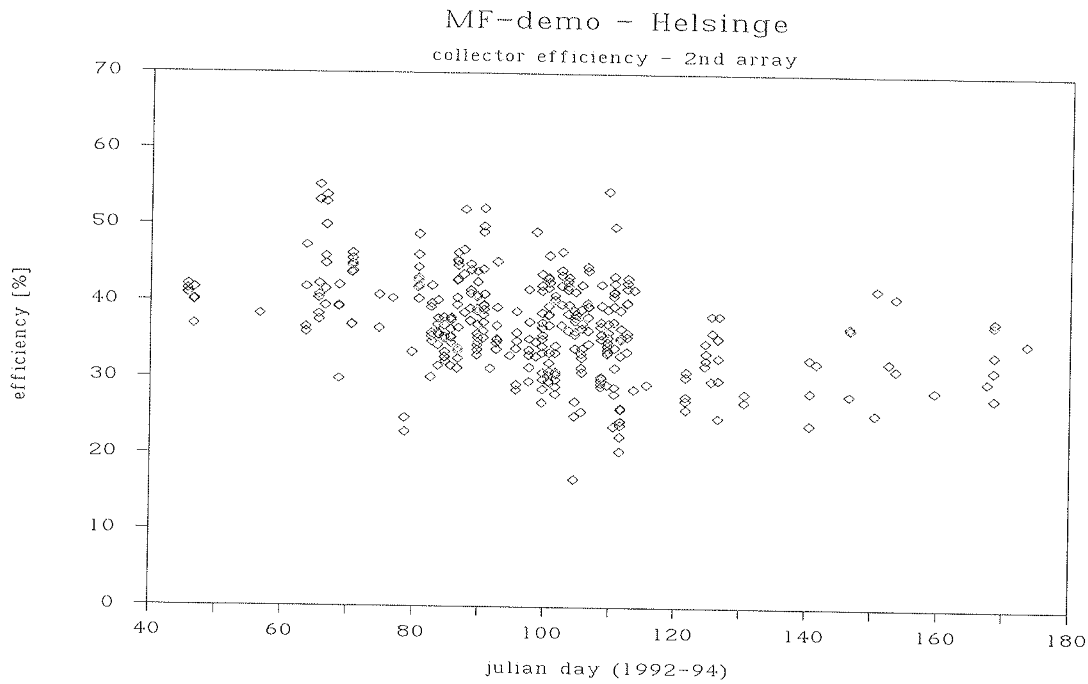

Figure 3.15. The efficiency of the second array of the MF-panel acting as solar collector. The second array supplies preheated air to room 2.

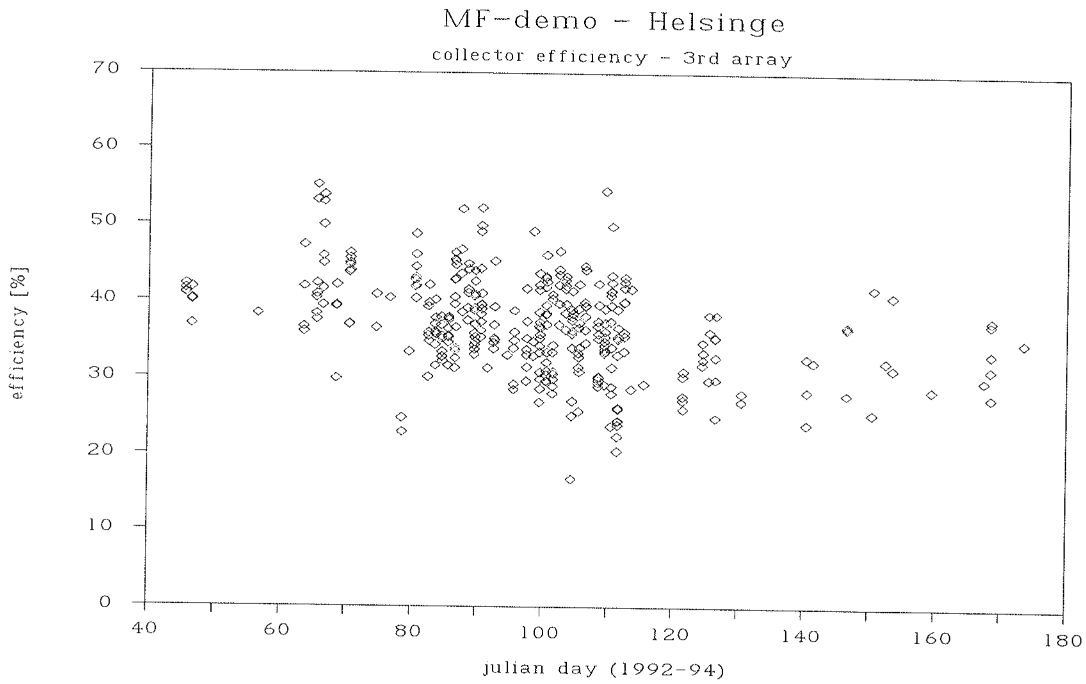

Figure 3.16. The efficiency of the third array of the MF-panel acting as solar collector. The third array supplies preheated air to room 3.

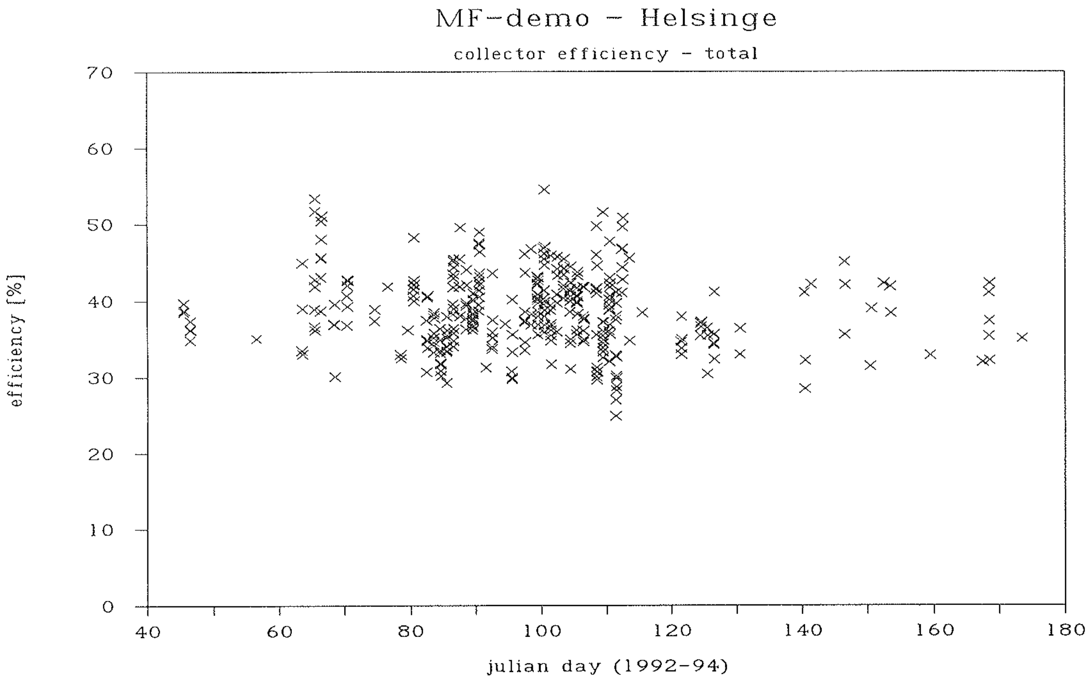

Figure 3.17. The overall efficiency of the total MF-panel acting as solar collector.

The mean values of the efficiency for the four cases shown in figures 3.13-17 are shown in table 3.1. The measured mean flow rate of the system was 28.2 m^3/m^2h.

	inlet	outlet
1st array:	39.6%	42.2%
2nd array:	36.8%	-
3rd array:	43.1%	-
Total:	38.8%	-

Table 3.1. The mean efficiencies of the MF-panel; "inlet" means that the efficiency is calculated based on the inlet temperatures to the rooms, while "outlet" means that the efficiency is calculated based on the outlet temperature from the MF-panel.

The reason for the difference between the efficiency of the three arrays is that the efficiency is very flow rate dependent - especially in this area as seen in figure 1.3. However, as seen in figure 3.18 the efficiency is even more flow rate dependent than shown in figure 1.3. The flow rate per m^2 was largest for the 3rd array and lowest for the 2nd array.

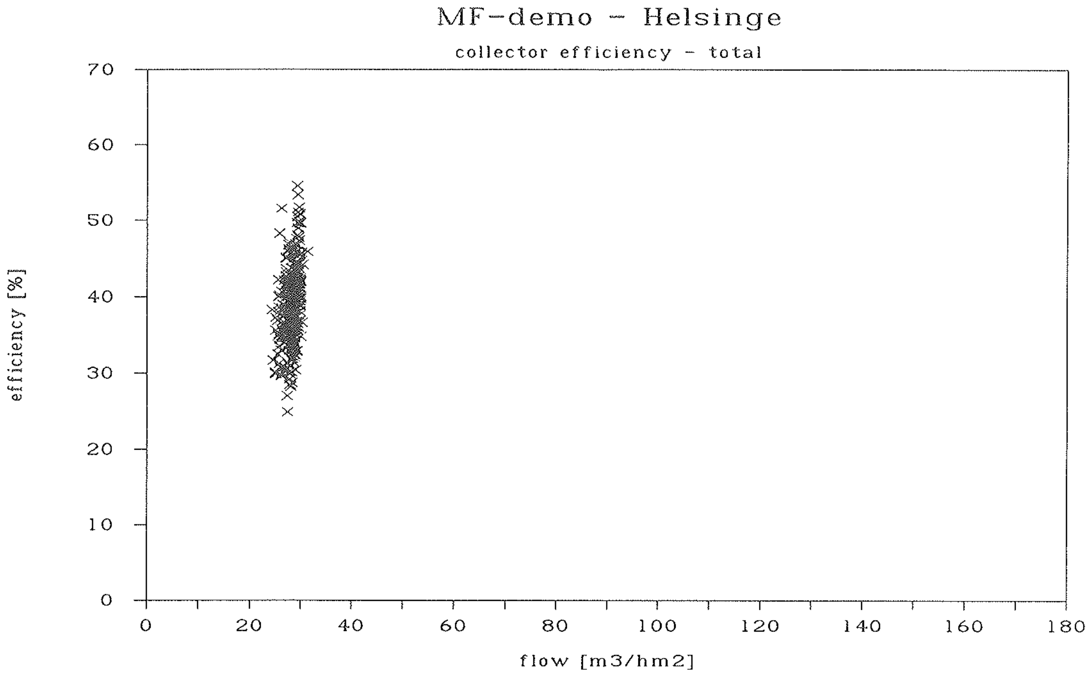

Figure 3.18. The total efficiency of the MF-panel with the same units on the x-axis as in figure 1.3 (see also figure 3.20).

The total efficiency is not dependent on the time of the year. However, the efficiencies of the 2nd and 3rd array seem to decrease going towards the summer, while the efficiency of the 1st array seems to increase. The reason for this may be that for the measurements close to summer, the heat demand for room 2 and 3 has been a bit less than for room 1. The flow may for that reason for some of the measured values not have been switched on during the whole half-hour periods. This gives a smaller flow rate and thereby a smaller efficiency, while the efficiency of array 1 increases, because it steals heat from array 2, when there is no flow in this array. The most obvious situations, where this has occurred, have been removed, however, some less infected measurements may still remain.

When comparing the mean efficiency of the two different ways of calculation for the 1st array it is seen that 6% of the energy is "lost" in the ducts. However, in section 3.1.6 it is shown that in mean the energy dissipated by the fans is 4-6%. So the measured efficiency of the MF-panel as solar collector (without the ducting) is approximately 10% higher than the measured efficiency of 38.8%.

In figure 1.3 it is seen that the efficiency of the prototype (without ducting) at a flow rate of 28 m^3/m^2h would have been approximately 32%. The efficiency of the actual MF-panel at Wewer's Brickyard was expected to be higher than the efficiency of the prototype, as the panel at the brickyard was longer than the prototype. In (Jensen, 1990a) a theory for the MF-panel acting as solar collector was developed. Figure 3.19 shows the comparison between the theory and the measurements for the prototype. The predicted efficiencies were as shown higher than the measured efficiencies. It was, however, judged that the theory could be used to estimate the increase in efficiency for a longer panel.

Based on the theory, the efficiency of the MF-panel at Wewer's Brickyard should have been around 12.5% higher than shown in figure 1.3 leading to an efficiency of 36%. This is still lower than the measured efficiency at the brickyard. An explanation could be that the theory overpredicts the efficiency of the tested prototype MF-panel leading to an underprediction of the efficiency for longer panels, as the calculated efficiency of the prototype is close to the theoretical maximum. However, this can only partly explain the difference between the efficiency of the prototype and the MF-panel at Wewer's Brickyard.

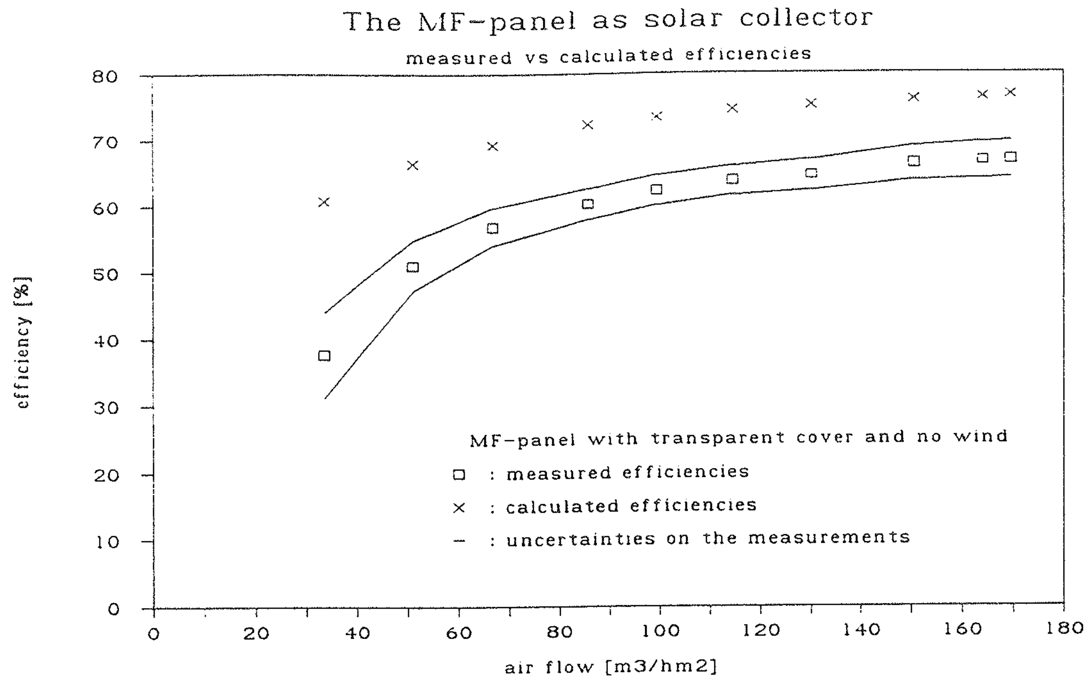

Figure 3.19. Measured and predicted efficiencies for the prototype acting as solar collector (Jensen, 1990a).

The measurements thus show that the MF-panel acting as solar collector under real weather conditions has a higher efficiency than could be expected from the investigations of the prototype.

The above-shown efficiencies for the prototype MF-panel have been measured under real weather conditions which means that many parameters have varied over time. This gives the opportunity to investigate the influence of these parameters on the efficiency of the MF-panel acting as solar collector - influences which could not be investigated in the artificial sun with stable conditions.

The influence of the flow rate, the solar radiation, the ambient temperature and the time of the day will be investigated. The investigation of the time of the day will give an impression on the transient behaviour of the MF-panel due to the heat capacity of the panel.

The influence of the flow rate on the total efficiency of the MF-panel has already been shown in figure 3.18. Figure 3.20 shows the same values with another scale on the x-axis. Figures 3.18 and 3.20 show that the MF-panel efficiency is very much dependent on the flow rate through the panel - much more than indicated from the test of the prototype - figure 1.3. This may partly be due to the transient behaviour of the MF-panel - see later.

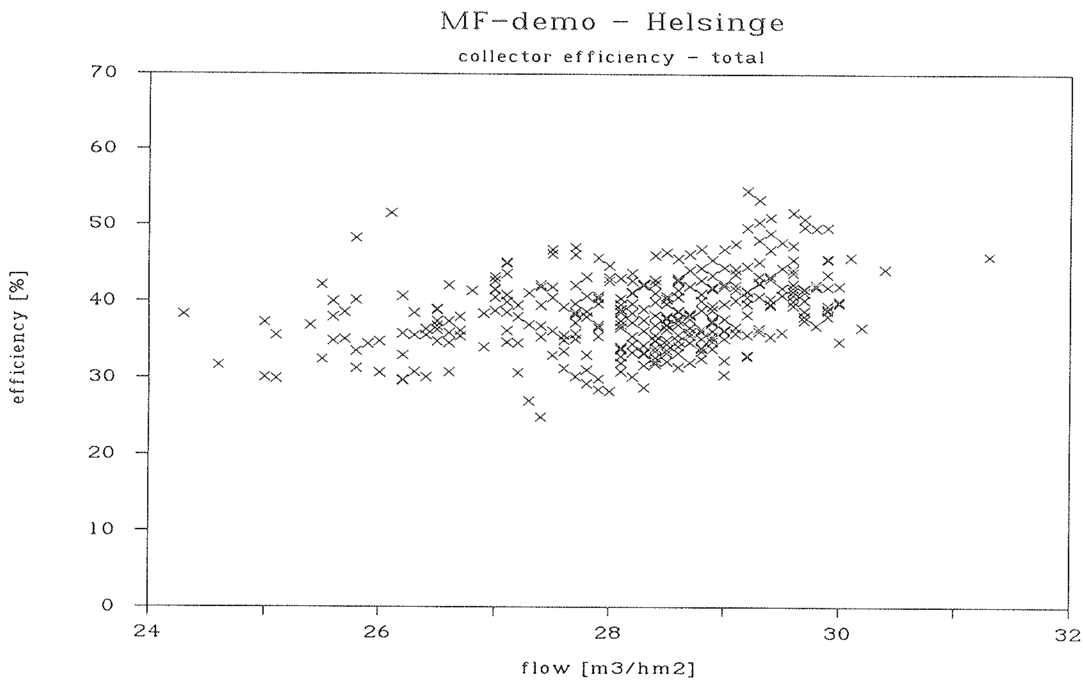

Figure 3.20. The overall efficiency of the MF-panel as solar collector, as a function of the flow rate through the panel.

Figure 3.21 shows the influence of the solar radiation on the MF-panel. It was assumed in (Jensen, 1990a) that the efficiency was independent on the level of radiation. This seems to be almost true - only a slight dependency is seen: A small decrease with increasing radiation level. It has not been possible, based on the measurements, to determine why there is this dependency. The dependency could be explained if the heat loss of the MF-panel is not linear dependent of the temperature level of the MF-panel - ie if the heat loss increases more rapidly than the temperature level.

Figure 3.22 shows the influence of the ambient temperature on the efficiency of the MF-panel acting as solar collector. As seen in the figure, the efficiency is not dependent of this parameter.

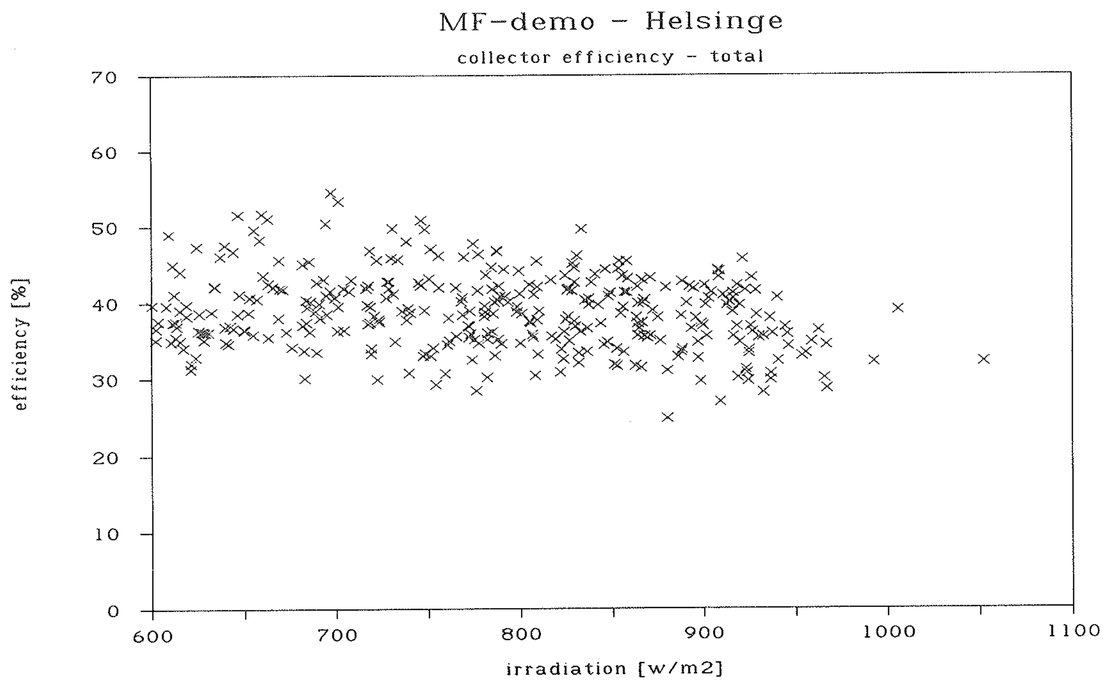

Figure 3.21. The overall efficiency of the MF-panel as solar collector, as a function of the solar radiation on the panel.

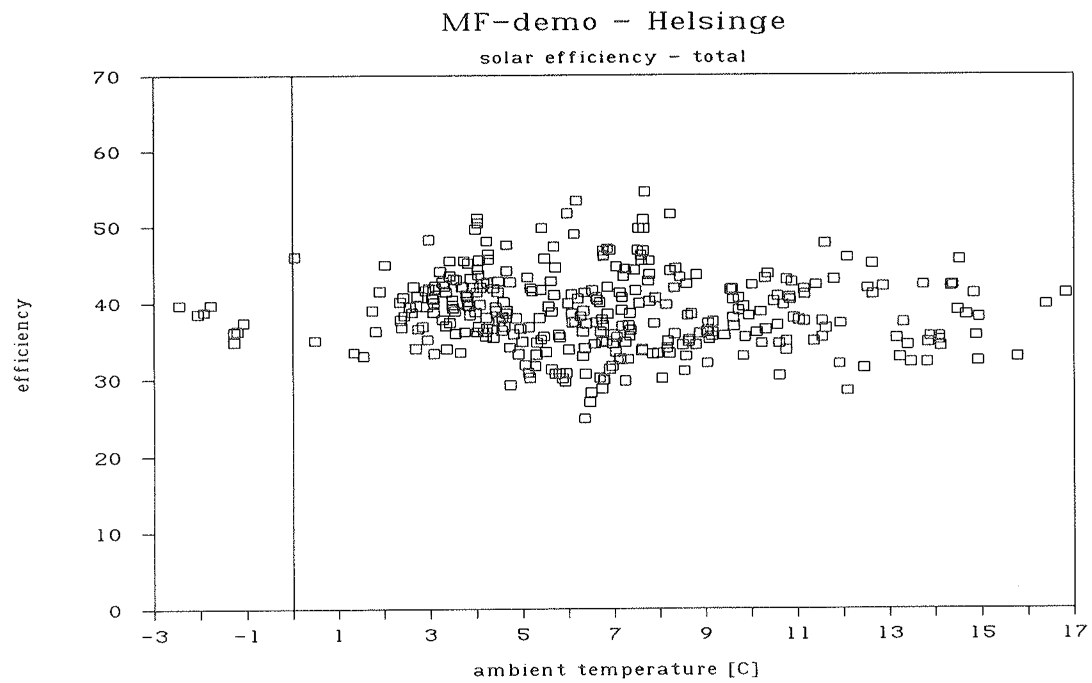

Figure 3.22. The overall efficiency of the MF-panel as solar collector, as a function of the ambient temperature.

Figure 3.23 shows the influence of the time of the day on the efficiency of the MF-panel. It seems that the efficiency increases over the day. This is shown more clearly in figure 3.24, showing the efficiency for three days in April 1993.

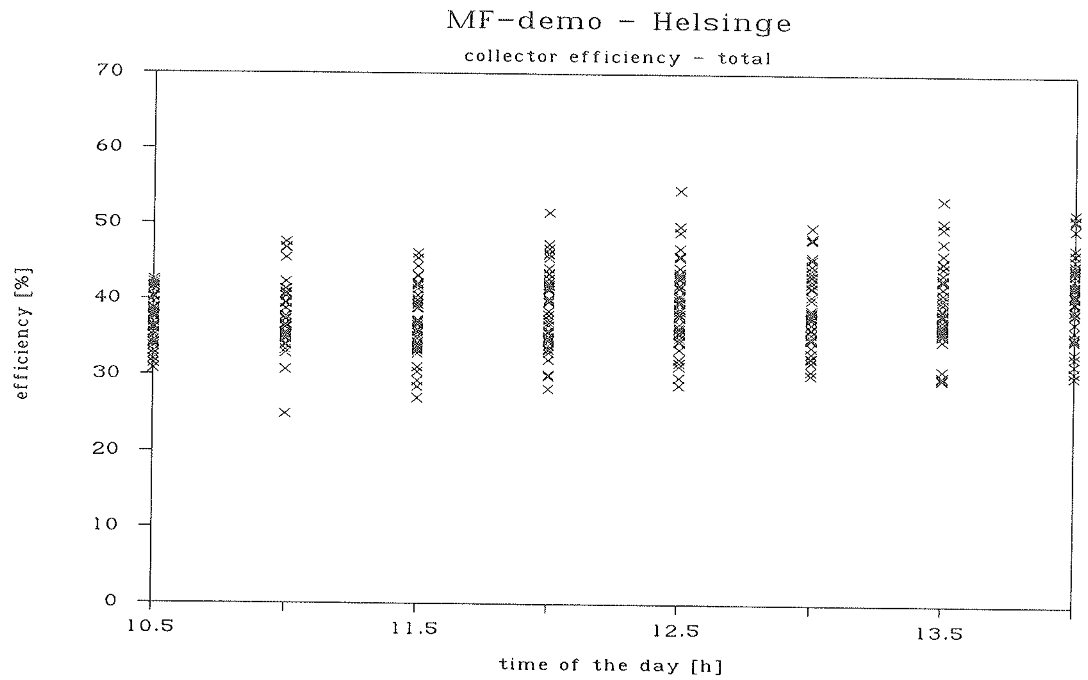

Figure 3.23. The overall efficiency of the MF-panel as solar collector, as a function of the time of the day.

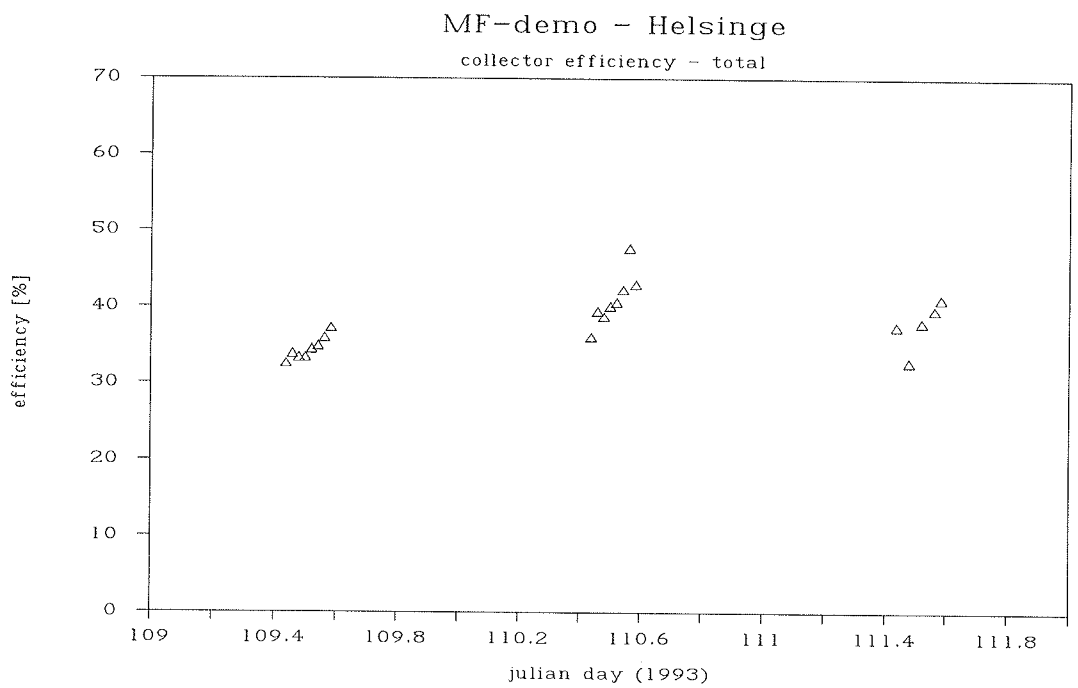

Figure 3.24. The overall efficiency of the MF-panel, as solar collector as a function of the time of the day for three days in April 1993.

The shown dependency of the time of the day is due to the heat capacity of the MF-panel. With increasing radiation on the MF-panel, not only the air temperature in the panel will increase, the whole construction will be raised to a higher temperature level. Energy is needed to increase the temperature of the construction resulting in a lower efficiency than for the steady state conditions shown in figure 1.3. When the radiation level decreases the construction will be cooled by the air stream leading to a higher temperature of the outlet air from the panel. This will increase the efficiency compared to steady state conditions.

The heat capacity of the MF-panel does not decrease the performance of the system, if the panel is installed in connection with a continuously running ventilation system. The heat lost during the heating-up of the MF-panel is later retrieved during the cooling-down of the panel. A high heat capacity may actually be an advantage as it may introduce a phase shift of the heat delivery to the building, so that it will be in less conflict with the direct heat gain from the sun through the windows of the building.

The present investigation of the efficiency of the MF-panel as solar collector has shown, that the performance of the panel under real weather conditions is higher than expected - approximately 18% higher. The investigation has revealed a high dependency of the efficiency on the flow rate of air through the panel. A small dependency of the solar radiation and the heat capacity of the MF-panel was further shown, while the efficiency is independent of the ambient temperature.

3.1.4. The Efficiency of the MF-panel as a Heat Exchanger

The efficiency of the MF-panel operating purely as a heat exchanger between fresh air and exhaust air is investigated in this section. The efficiency of the MF-panel acting as a heat exchanger is defined as the energy delivered to the rooms (calculated on basis of the ambient temperature and the inlet temperature to the rooms) divided by the energy extracted from the rooms (calculated on basis of the room outlet temperature and the ambient temperature).

The investigation of the MF-panel acting as a heat exchanger was made very difficult due to the way the building was used. The MF-panel system was as already mentioned normally not allowed to operate as a heat exchanger. To overcome this problem it was decided to carry out special-purpose measurements where the MF-panel was forced to operate as a heat exchanger. These measurements could, however, only be carried out during periods when it did not disturb the production in the building or create any discomfort for the workers.

In order to determine the efficiency of the MF-panel as heat exchanger with a low uncertainly, it is necessary to have a high difference between the room temperature and the ambient temperature. This means that (even with a high efficiency of the exchanger) cold air will be let down to the workers leading to discomfort. So the special-purpose measurements for determination of the efficiency of the MF-panel as heat exchanger could only be performed during winter-time in periods with the workers out of the workshop, ie during weekends and holidays.

However, due to the changes in production in the workshop, and further the close-down of another brickyard, it was not possible to cover the demand for brick beams during normal working hours. The workers had, therefore, a lot of overtime, ie often worked during weekends. Due to the production of special-purpose bricks for English manors it was furthermore often not possible to run the MF-panel in heat exchanger mode, as this would dry out the bricks too fast. It has therefore not been possible to obtain much data for the investigation of the MF-panel operating as a heat exchanger.

It was possible to perform a special-purpose experiment during the Easter 1993. However, it seems that the switches for forcing the MF-panel to operate as desired were not operated correctly. The data from this period could, therefore, not be used for the contemplated investigation.

It was difficult to find other periods where the special-purpose experiments could be carried out. One possibility was during Christmas 1993. However, during this period the PC was broken down. Only one period of measurements has been obtained - a few days during Easter 1994.

However, array 1 did, for some unexplainable reason, not operate as heat exchanger but only as collector during this period. Measurements have thus only been obtained for array 2 connected to room 2. These measurements are investigated in the following.

Figure 3.25 shows the efficiency of the MF-panel (array 2) for one and a half day in April 1994. The figure shows that the efficiency of the MF-panel as heat exchanger during day-time is different from the efficiency during night-time. This difference is caused by the solar radiation as shown in figure 3.26. In the following first the efficiency during night-time will be investigated, then the influence of the solar radiation on the efficiency of the MF-panel as heat exchanger.

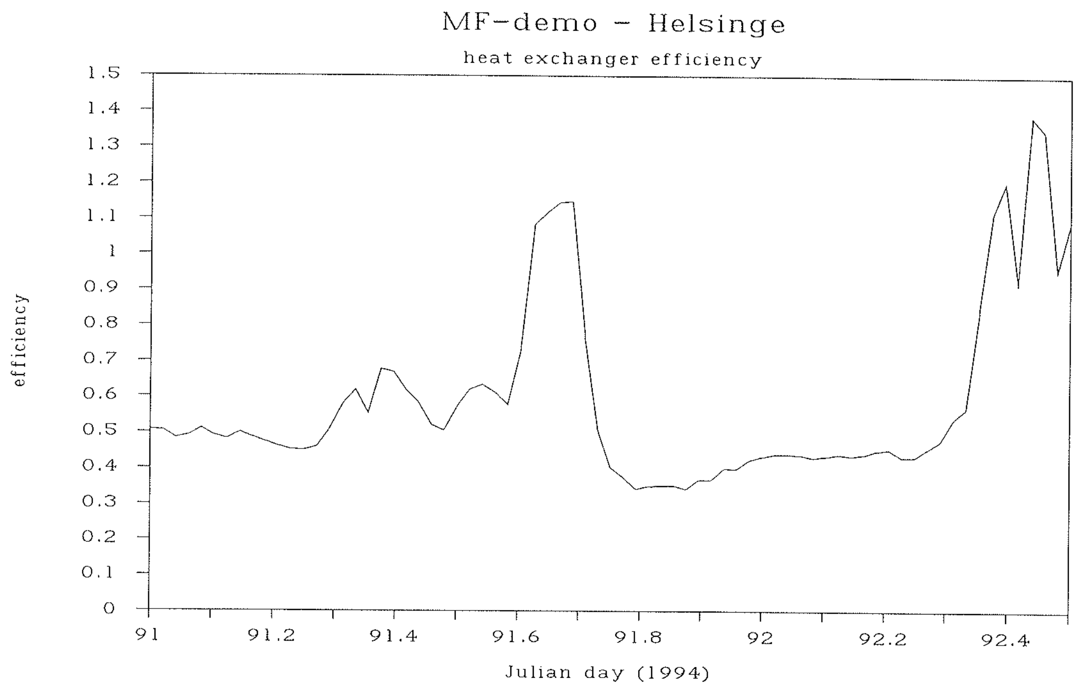

Figure 3.25. The efficiency of the MF-panel (array 2) as heat exchanger for a short period in April 1994.

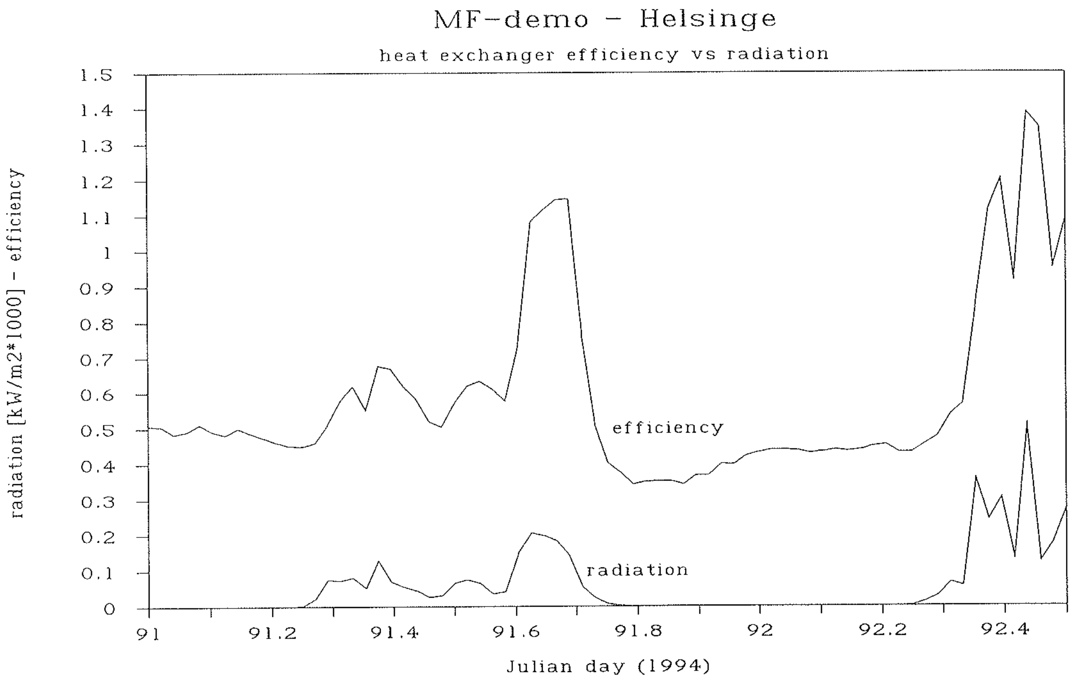

Figure 3.26. The efficiency of the MF-panel as heat exchanger compared with the solar radiation on the panel.

Figure 3.27 shows the night-time efficiency of the MF-panel as heat exchanger, ie during periods without solar radiation.

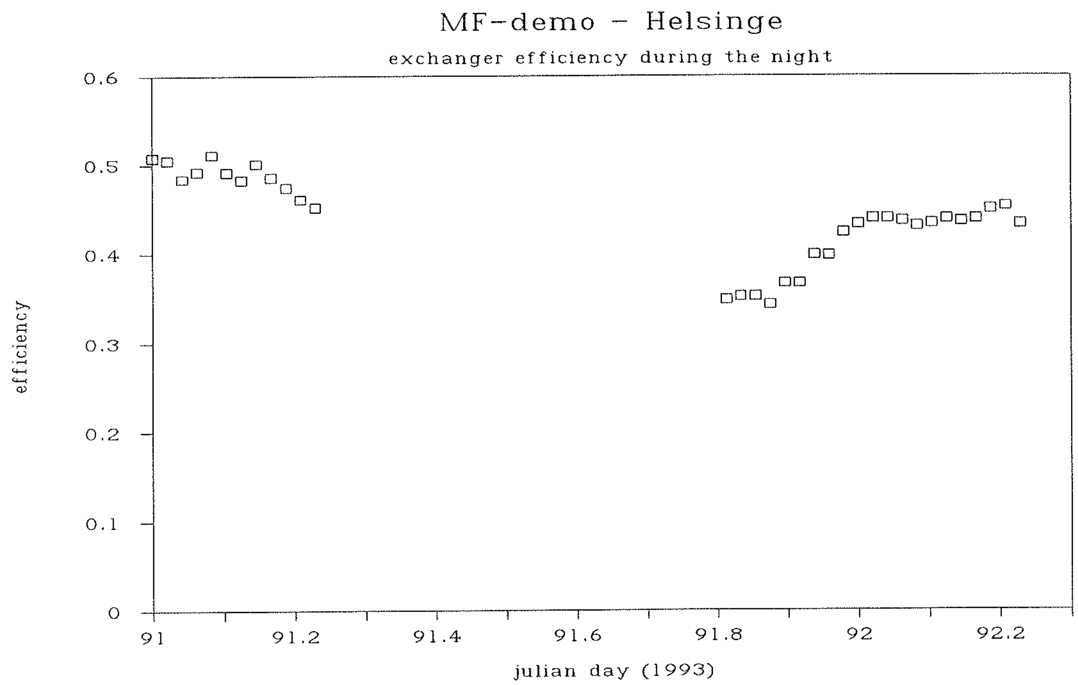

Figure 3.27. The night-time efficiency of the MF-panel as heat exchanger.

The mean of the measured efficiency values from figure 3.27 is found to be 44%. The efficiency is found for a mean flow rate of 19 m^3/m^2h. The figure shows, however, that the efficiency is not a constant. In figure 3.28 some of the parameters for calculating the efficiency are shown. When comparing figures 3.27 and 3.28 it is seen that there is a high degree of correlation between the efficiency and the temperature difference between the room temperature and the ambient temperature. This correlation is shown more clearly in figure 3.29.

From figure 3.29 it is seen that there is a linear correlation between the efficiency and the temperature difference between the room temperature and the ambient temperature. The dependency of the efficiency on the temperature difference is:

$$eff = -0.05 + 0.039\ \Delta T$$

where: ΔT is the temperature difference between the room temperature and the ambient temperature.

This line is also shown in figure 3.29.

The mean value of the efficiency of the MF-panel as heat exchanger was found to be 44%. This is much higher than shown in figure 1.4. The reason for this is again, that the MF-panel was longer than the prototype. A theory for the MF-panel as heat exchanger based on the investigation of the prototype was developed in (Jensen, 1990a). A comparison between measured and predicted values for the prototype is shown in figure 3.30. It was, as for the solar collector, judged that the theory was good enough to estimate the increase of the efficiency due to the longer MF-panel.

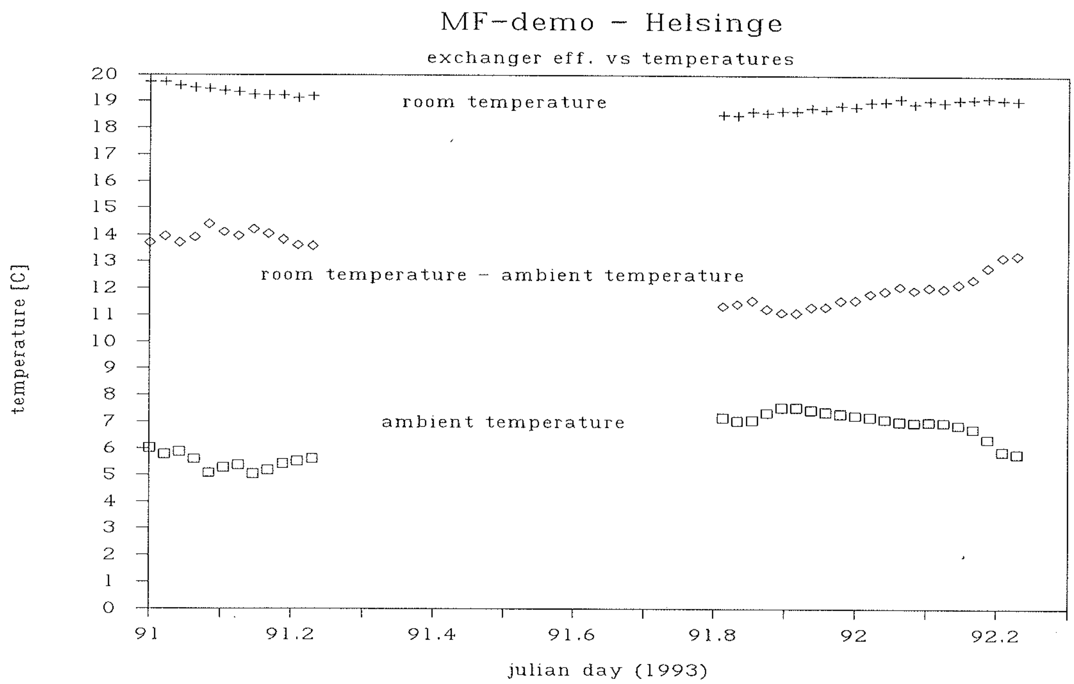

Figure 3.28. Some important parameters for determination of the efficiency of the MF-panel as heat exchanger.

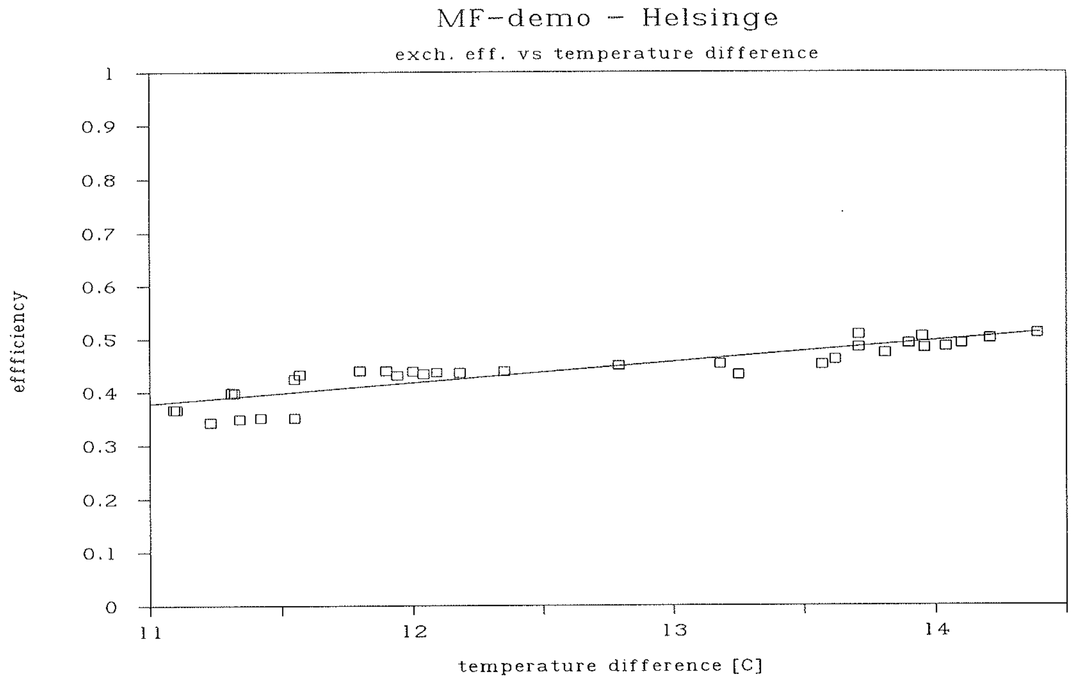

Figure 3.29. The efficiency of the MF-panel as heat exchanger dependent on the difference between the room temperature and the ambient temperature.

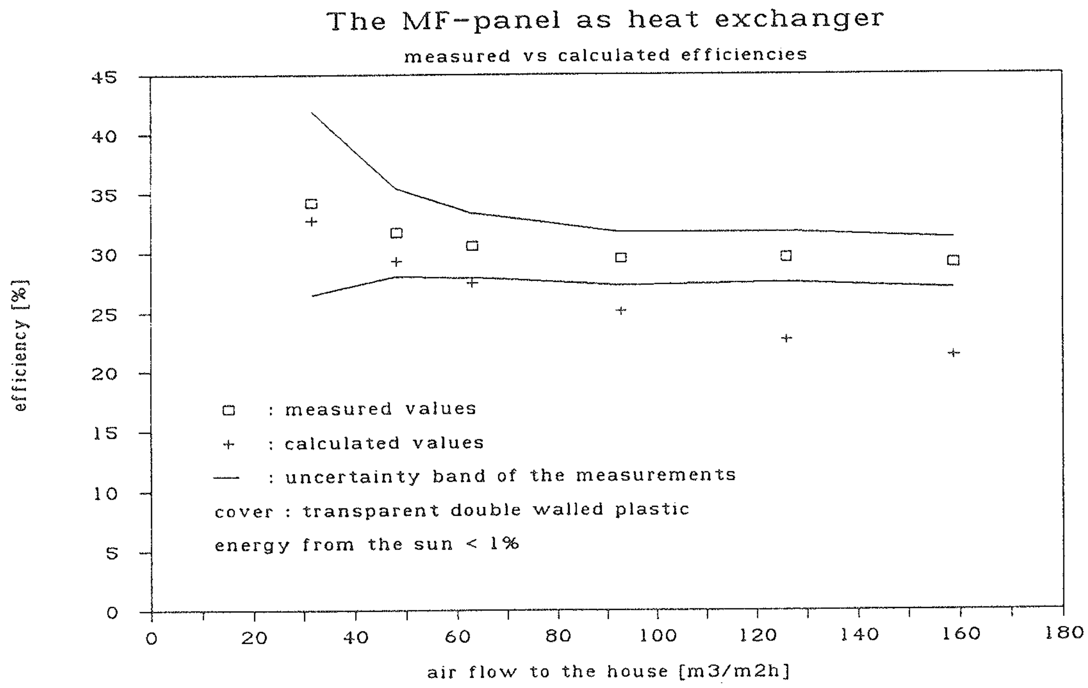

Figure 3.30. Measured and predicted values for the prototype of the MF-panel (Jensen, 1990a).

Based on the theory in (Jensen, 1990a) the efficiency of the prototype as heat exchanger with the same length as at Wewer's Brickyard is calculated to be 44%, which is the same as measured on the actual MF-panel at Wewer's Brickyard. The measured efficiency is based on the inlet and outlet temperature of the rooms while the measured efficiency of the prototype was based on the inlet and outlet temperature of the MF-panel. The efficiency of the MF-panel at Wewer's Brickyard has thus a higher efficiency than could be predicted based on the experience from the prototype. How much higher the efficiency is cannot be determined from the measurements, as array 1, where the special-purpose temperature sensors in the inlet and outlet of the MF-panel were located, was not in operation. The energy dissipated by the fans in the inlet and outlet ducts is the same, but as the heat loss from the outlet ducts is higher than from the inlet ducts, due to the difference in temperature level, the efficiency of the MF-panel as heat exchanger (without ducting) may therefore be several percent higher than directly measured and expected. It was unfortunately not possible to verify this in the present project.

The efficiency of the prototype was found at a mean temperature difference of approximately 15 K, while the mean difference at the brickyard was approximately 12.6 K. According to figure 3.29 the efficiency of the MF-panel may thus furthermore have been 20% higher than for the prototype.

Figure 3.26 shows that the efficiency of the MF-panel as heat exchanger is very much dependent on the solar radiation. This is shown more clearly in figure 3.31 where the day-time efficiency is shown dependent on the solar radiation on the MF-panel.

Figure 3.31 shows that the efficiency of the MF-panel is more than doubled even at the rather low solar radiation level which occurred during this measuring period. This shows, as was already found at the investigation of the prototype of the MF-panel, that the operation of the MF-panel should switch from the heat exchanger mode to the collector mode at a certain radiation level. This is shown more clearly in figure 3.32, where the measured energy delivered from the MF-panel as heat exchanger is compared with the predicted energy delivered from the MF-panel acting as a solar collector when it is assumed that the efficiency of the solar collector (incl ducting) is 38.8%.

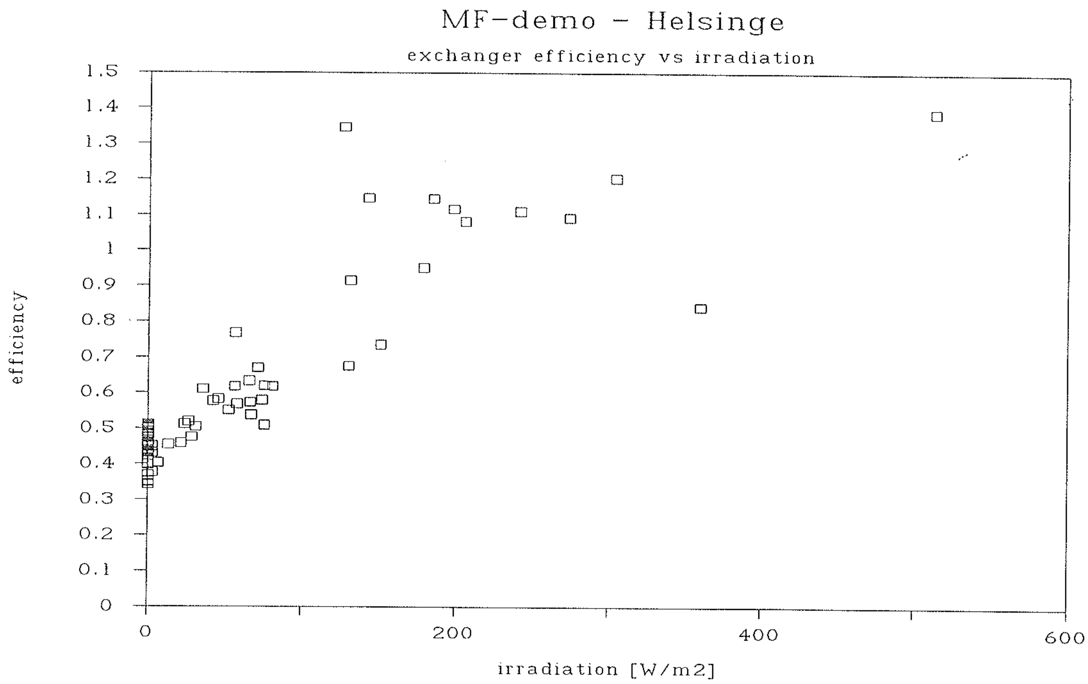

Figure 3.31. The efficiency of the MF-panel as heat exchanger dependent on the radiation on the MF-panel.

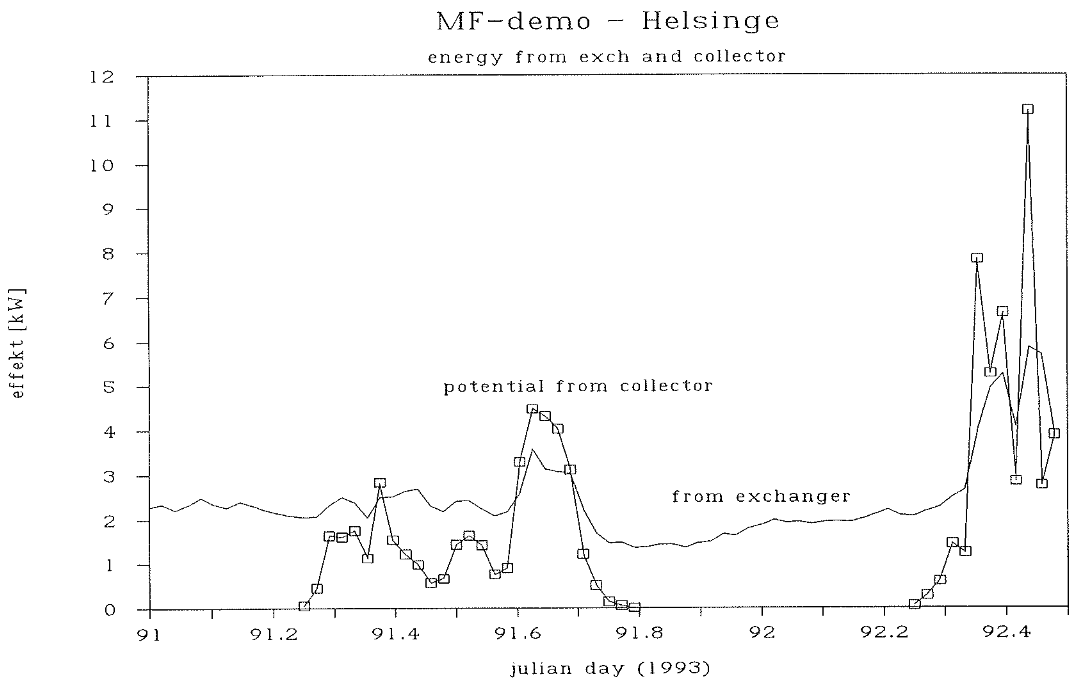

Figure 3.32. The actual measured energy delivered from the MF-panel as heat exchanger compared with the estimated amount of energy from the MF-panel if it has acted as a solar collector.

The switch between the two operation modes should be based on the radiation level as well as on the temperature level between indoor and ambient. The latter because the amount of energy from the MF-panel as heat exchanger is very much dependent on this temperature difference. It is maybe possible to control the MF-panel only dependent on the temperature level at the top of the MF-panel. This, however, demands further investigations either on an actual system or by use of computer simulations or maybe both.

However, as the efficiency of the MF-panel as solar collector is very flow rate dependent, and the efficiency of the MF-panel as both solar collector and heat exchanger is very dependent on the actual length of the panel, the set point for switching between the two operation modes has to be determined for each case separately.

Figures 3.33-34 show the temperature profiles in the MF-panel during the above-investigated period, using the special-purpose temperature sensors shown in figure 2.46.

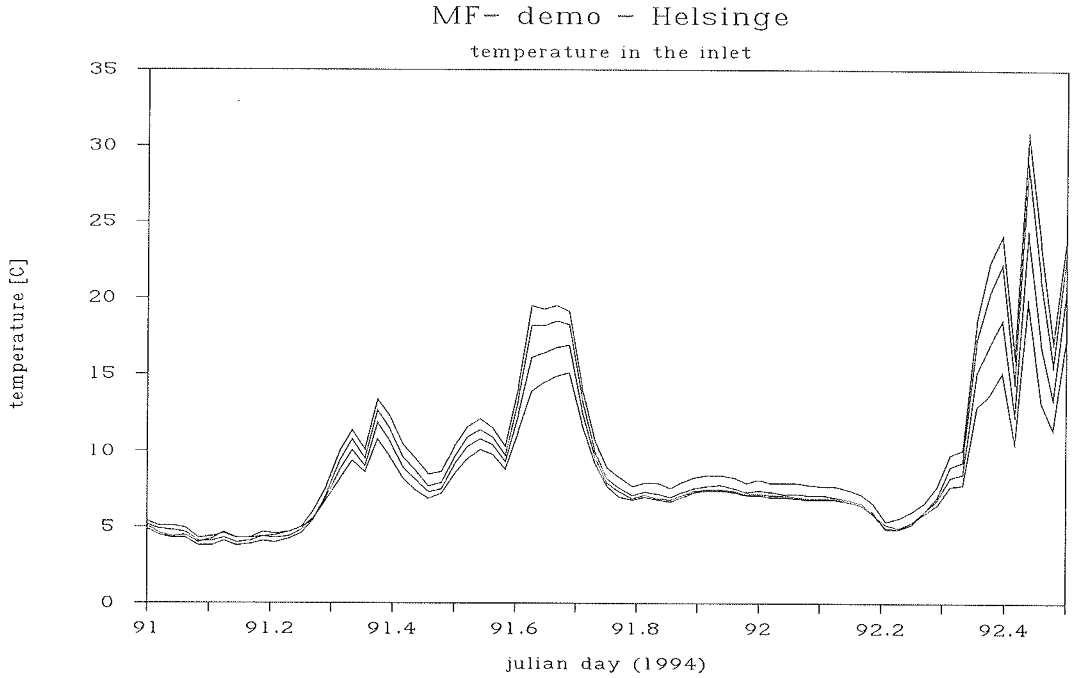

Figure 3.33. The temperature between the cover and the absorber of the MF-panel.

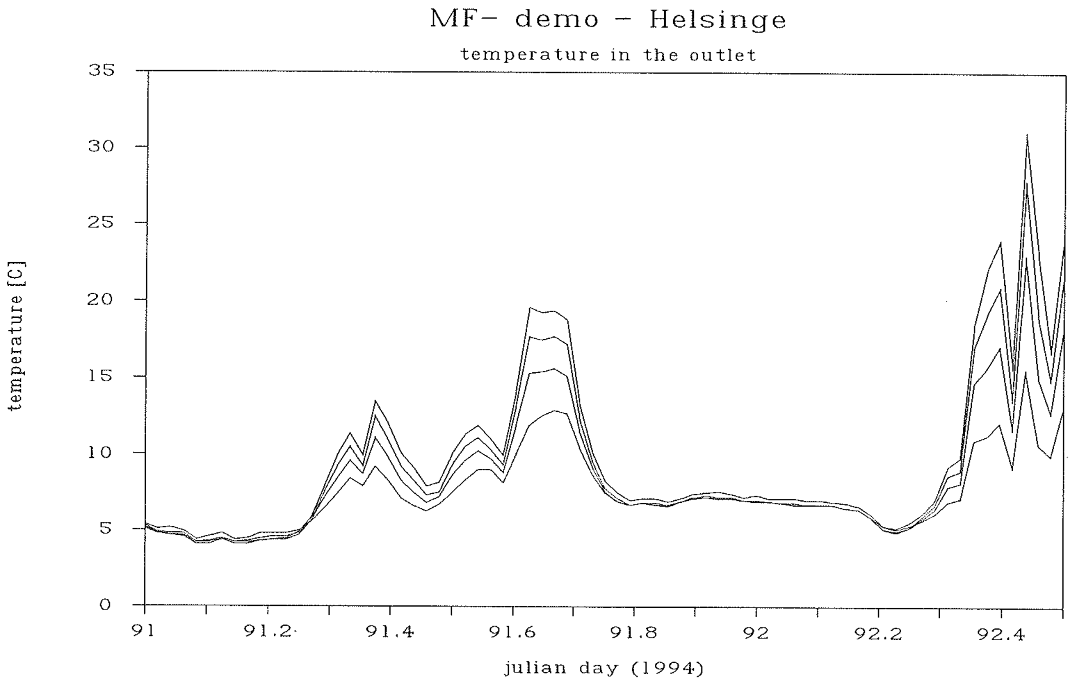

Figure 3.34. The temperature between the absorber and the insulation of the MF-panel.

The present investigation of the MF-panel acting as a heat exchanger has shown that the efficiency is higher than could be expected. The investigations further showed that the efficiency seems to be very dependent on the temperature difference between indoor and ambient. The investigations also showed that in order to maximize the gain from the MF-panel it is necessary to shift between the two operation modes - heat exchanger and collector mode. How best to control this shift needs, however, to be investigated further; this could probably be done by computer simulations.

3.1.5. The Bypasses for the Cooling of the MF-panel

On figures 2.28 and 2.37 it was shown that three bypasses were connected to the top of the MF-panel in order to cool the panel during summer-time by natural circulation by use of the stack effect. In this section it is investigated if the bypasses have cooled the panel as intended.

A motor damper was installed in each bypass. The motor dampers were, as described in section 2.2.3, controlled by a thermostat with the sensor located in the top of the MF-panel. The thermostat was adjusted to open the dampers of the bypasses at a temperature in the top of the MF-panel of 60°C.

The intention with the dampers was to ensure that the maximum temperature of the MF-panel did not exceed 100°C. Inspections at the brickyard showed, that the bypasses did let hot air out of the MF-panel at high temperatures in the MF-panel. However, the bypasses did not achieve to keep the temperature level of the MF-panel below 100°C.

An investigation of the measured data has shown that the temperature of the top temperature sensors shown in figure 2.46 often exceeded 100°C. The temperature of the MF-panel (1.2 m from the top) did eg in June 1993 (Julian day 155) exceed 124°C. This is shown in figure 3.35.

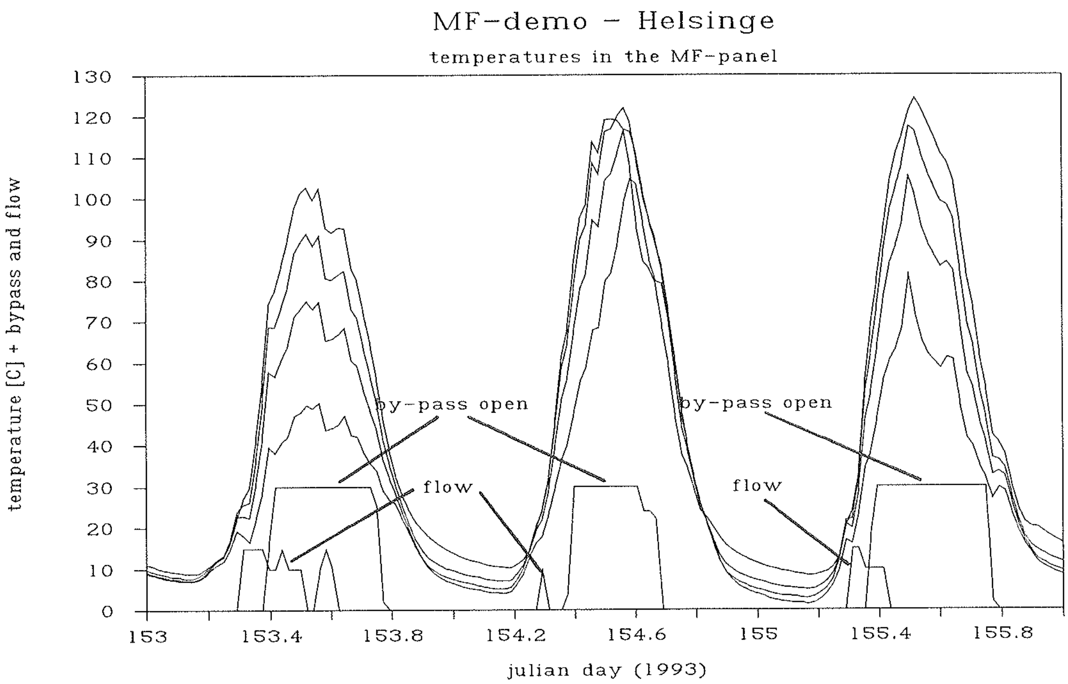

Figure 3.35. The temperatures in the MF-panel during three days in June 1993 together with an indication of the flow rates and status open/closed for the bypasses.

Figure 3.35 shows the readings from the four temperature sensors shown in figure 2.46 for three days in June 1993. The figure further indicates when the bypasses have been open and the flow rate in the MF-panel due to heat delivery to the rooms. "30" means that the bypasses have been open during the whole half-hour period. For the flow in the MF-panel: "5" tells that flow only occurred in array 1, "10" that there was only flow in array 2, while "15" means that there was flow in both arrays. Figure 3.36 shows the solar radiation and ambient temperature for the same period as figure 3.35.

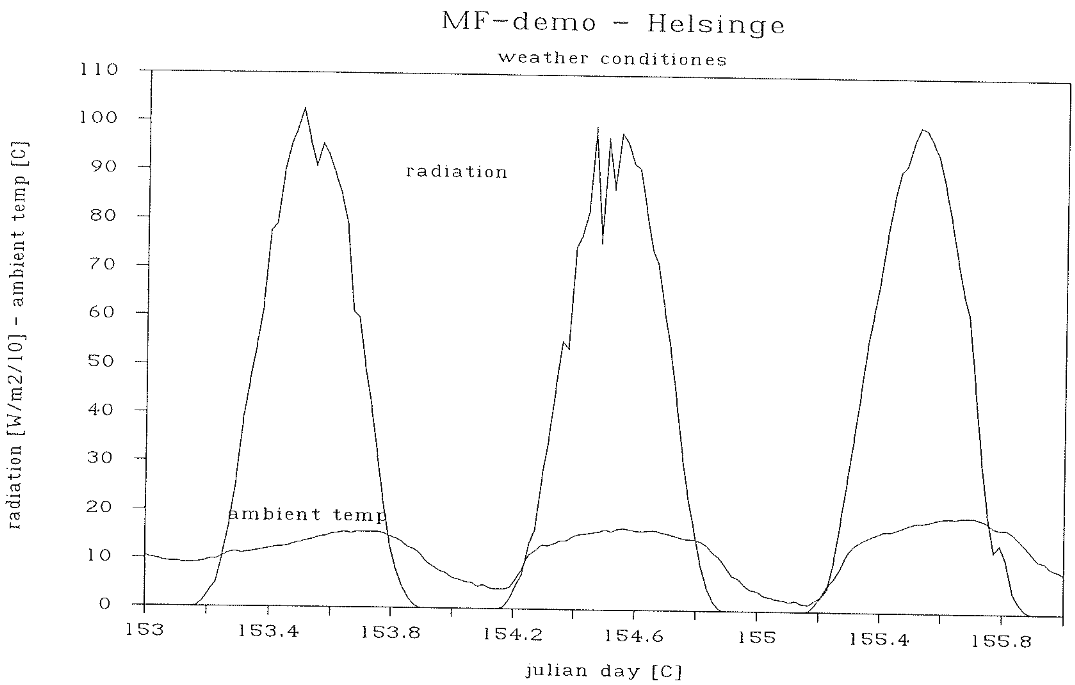

Figure 3.36. The solar radiation and ambient temperature during the same period as figure 3.35.

Figures 3.37-3.39 show the three days separately.

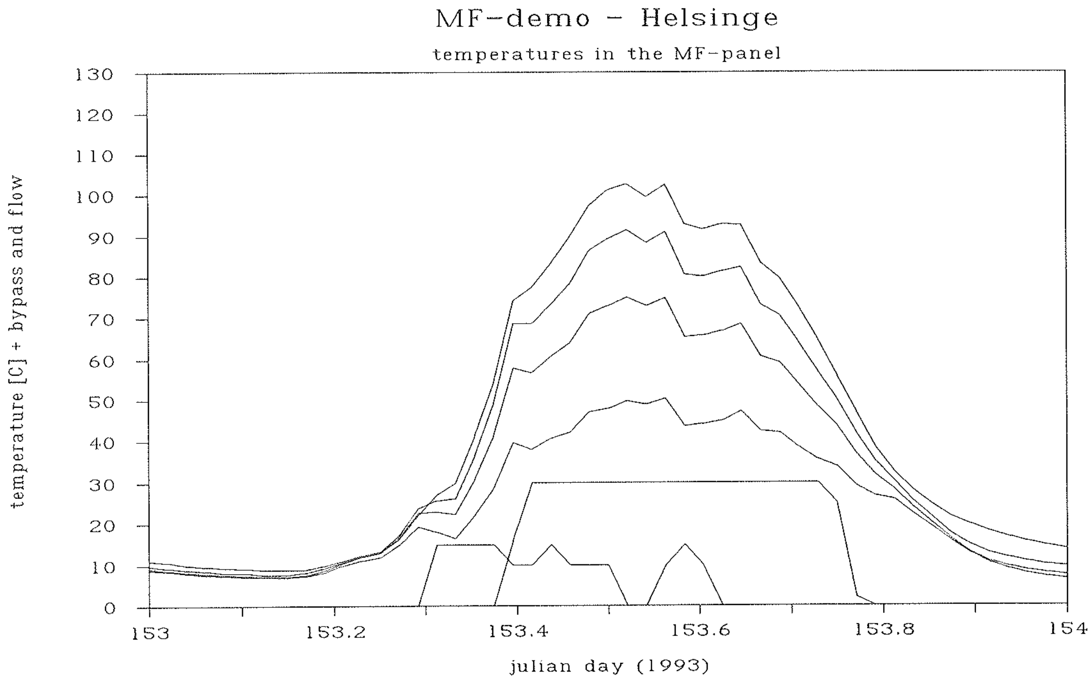

Figure 3.37. The temperatures in the MF-panel during a day in June 1993 together with an indication of the flow rates and status open/closed for the bypasses.

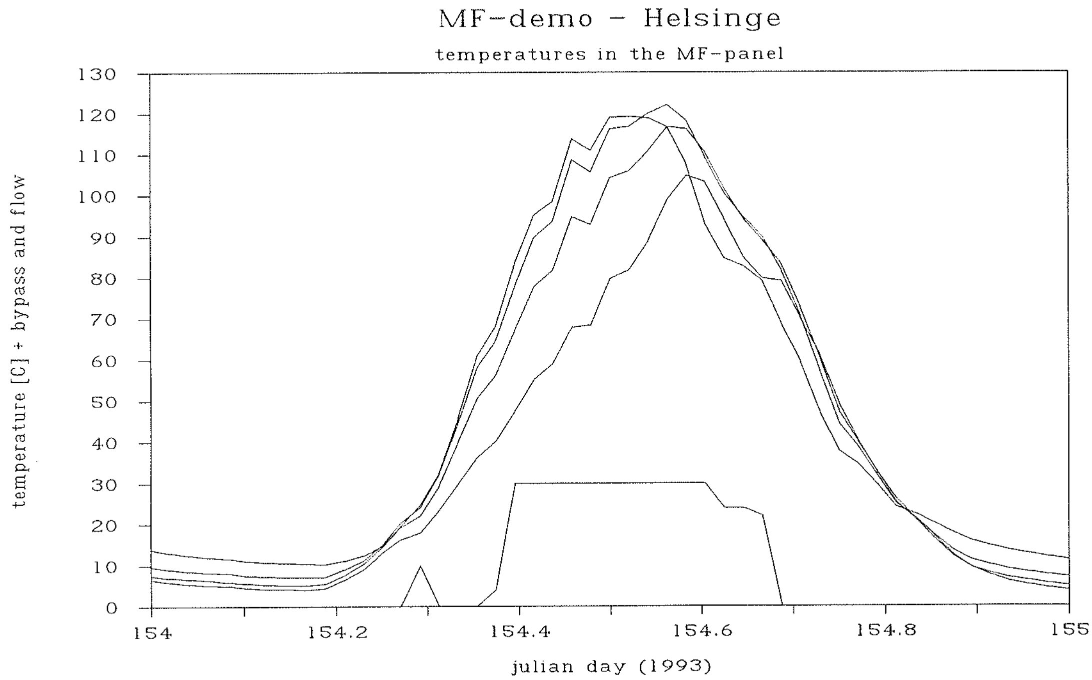

Figure 3.38. The temperatures in the MF-panel during a day in June 1993 together with an indication of the flow rates and status open/closed for the bypasses.

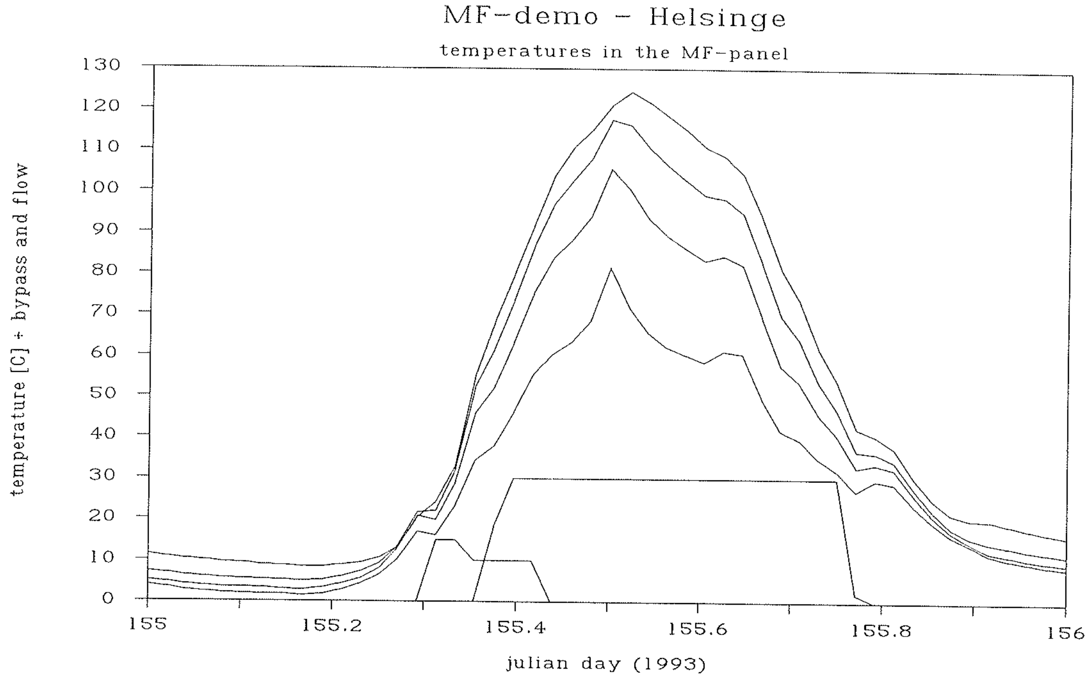

Figure 3.39. The temperatures in the MF-panel during a day in June 1993 together with an indication of the flow rates and status open/closed for the bypasses.

Figures 3.35-39 show that the temperature level of the MF-panel is hardly influenced by the opening of the bypasses. The figures further show that a flow rate in the same magnitude as the flow rate created by the fans is necessary in order to prevent the temperature of the MF-panel to exceed 100°C.

It is thus necessary either to ensure that the materials of the MF-panel can withstand the high temperature level or that the panel is cooled actively by fans. The latter requires, however, the use of electricity, so the first solution is to be preferred.

3.1.6. Electricity Requirement for the Fans

The above section leads to the discussion of the electricity requirements for the fans in the MF-panel system. The MF-panel should be installed in connection with a ventilation system that has to be installed in the building anyway or already exists. The pressure drop across the MF-panel is not very high (Jensen, 1990a) so the installation of the MF-panel in an existing ventilation system will hardly influence the electricity demand of the fans in the ventilation system.

The electricity demand for running the fans of the MF-panel system will nevertheless be investigated in this section.

The electricity demand of the fans for the year investigated in section 3.1.1 based on the measured performance of the system and readings of the kWh-meter shown in figure 2.40 is found to be approximately 4 and 6% of the performance of the system, depending on which of the two definitions from section 3.1.1 is used. Investigations of the measured temperature increase over the fan in the duct of "in 3" (figures 2.29 and 2.44) for April 1993 have shown that the mean temperature increase during this month was 0.6°C, which corresponds to an electricity demand for the fan of 13% of the performance of array 1. This latter measurement is, however, very uncertain, and can not really be used as an indication for the electricity demand of the MF-panel, but it indicates that the main part of the electricity for the fans is transferred to the air stream as heat. This latter was expected as the fans have the motors located in the ducts.

3.2. The Performance of the MF-panel in a more Ideal Building

The previous sections showed the measured performance of the MF-panel system on a workshop at Wewer's Brickyard in Helsinge, Denmark. The workshop was as already explained not ideal for the demonstration of the MF-panel concept, and changes in the working routine within the workshop made the building even less applicable for this purpose. However, it was judged that it would be possible to extrapolate from the workshop to a more ideal building. This will be done in this section.

The performance of the MF-panel is, as already shown, very dependent on the length of the panel, on the flow rate of air through the panel but also on the heating demand of the building. The performance of an MF-panel as on the workshop (the same flow rates through the MF-panel) will first be evaluated on a building with a continuous ventilation demand. After that the performance with a more ideal flow rate through the MF-panel will be found.

The starting point is an MF-panel system with a length of the MF-panel as on the workshop at Wewer's Brickyard, ie 6.0 m. The performance of the MF-panel is very dependent on the heating demand of the building. As the heat demand of no actual building was available, it was decided to used the same conditions as in (Jensen, 1990a).

One of the heat demands used in (Jensen, 1990a) was a data base containing the hourly heat demands for a new single-family house insulated according to the Danish standards for insulation BR-82 (The Danish Ministry of Housing, 1983). The net space heat demand is the gross space heat demand minus the utilized free heat gain from persons, electric appliances and the solar radiation through windows (Lawaetz and Jørgensen, 1977). There is no heat demand during the summer - May-September. The building has a continuous ventilation demand of 0.4 air changes per hour equal to 122 m^3/h. The yearly net heat demand for this building is 12,400 kWh. The monthly heat demands are shown in figure 3.40.

It is assumed that the performance of the MF-panel per m^2 for the above-mentioned heat demand may also give a realistic idea of the performance of the MF-panel installed in other buildings, eg multi-storey buildings.

The dependency of the transmittance through the cover of the MF-panel on the incidence angle of the solar radiation has been taken into account in (Jensen, 1990a). However, the investigations in (Jensen, 1990a) did not disclose 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 plate through which the heat exchange between the fresh air and exhaust air is also taking place. During periods with low solar radiation, so low that it is most profitable to use the MF-panel as heat exchanger, the energy gain from the panel is smaller than the sum of the possible energy gain from the exchanger and the solar collector. It has unfortunately not been possible to determine this interaction based on the measurements from the demonstration project, due to too little data in this field. Figure 3.41 shows the obtained measurements.

Figure 3.41 shows the reduction in the gained energy from the MF-panel as solar collector when operating in heat exchanger mode. The reduction is calculated in the following way: From the energy gain from the MF-panel working as combined heat exchanger and solar collector, during the period investigated in section 3.1.3 (a period with solar radiation) is subtracted the expected energy gain from the MF-panel as a heat exchanger (with an efficiency of 44%). The result is the extra gain obtained from the solar radiation. This extra gain is divided by the gain which could have been expected if the MF-panel had acted purely as a solar collector with an efficiency of 38.8%.

When comparing figures 3.26 and 3.32 it is seen that for this period the shift in operation between collector and exchanger mode should have happened at a solar radiation of about 100 W/m². Figure 3.41 does not give a clear picture, ie the measuring points are very scattered. The figure shows, however, that the reduction increases with increasing radiation level. This is because the incoming solar heated air is cooled by the exhaust air. The mean value of the reduction at a solar radiation level lower than 100 W/m² is 50%. This value will be used in the following.

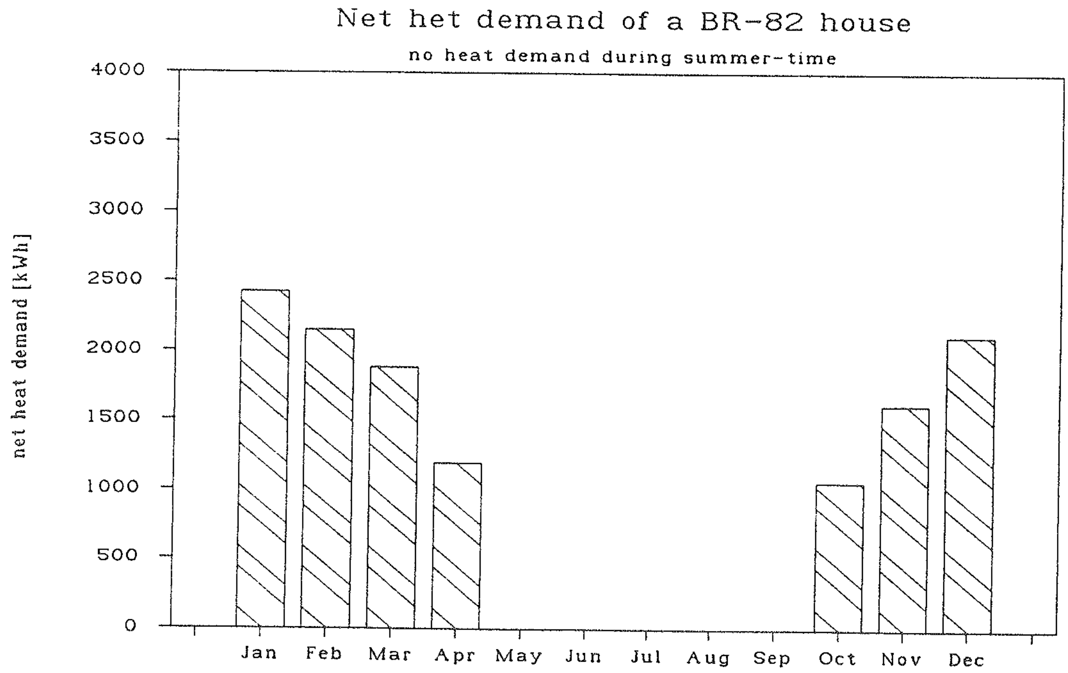

Figure 3.40. The heat demand per month for a BR-82 house (Jensen, 1990a).

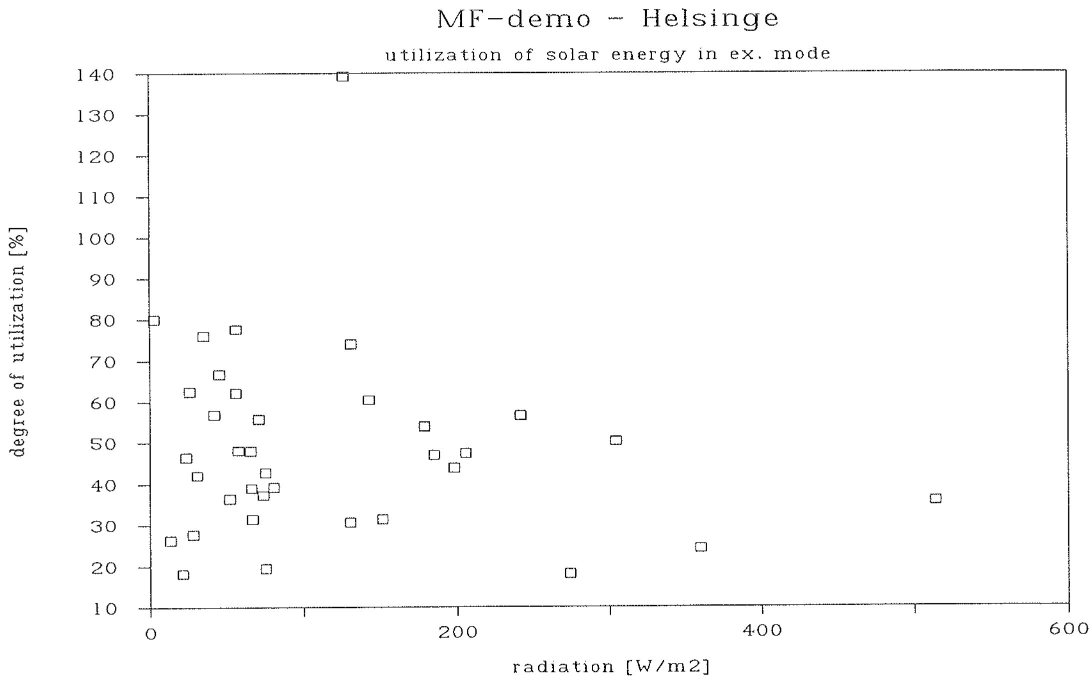

Figure 3.41. The utilization of solar energy when the MF-panel is working as combined collector and heat exchanger. The degree of utilization is the extra gain as solar collector divided by the performance as pure solar collector (further described on the previous page).

To overcome the above problem, with the missing knowledge of the interaction between the two operation modes, two parallel series of simulations have been carried out in (Jensen, 1990a) - an optimistic and a pessimistic simulation series. In the optimistic series it is assumed that there is no reduction in the collected solar energy when the MF-panel is in heat exchanger mode. In the pessimistic series it is assumed that non of the collected solar energy, when the MF-panel is in exchanger mode, is utilized. Based on figure 3.41 it seems that the real performance is to be found as a mean of the two simulation series.

Figures 3.42-43 show the results from the simulations in (Jensen, 1990a). It is here assumed, that there is no traditional heat recovery unit in the ventilation system. Such a unit would lower the performance of the MF-panel considerably.

In the demonstration project, the flow rate was 28 m^3/m^2h in collector mode while it in heat exchanger mode was 19 m^3/m^2h. In order to use figures 3.42-43 it is necessary to calculate the equivalent area of the MF-panel. In figures 3.42-43 the flow rate was 122 m^3/h. This means that the values for the collector mode should be found at an area of 122/28 = 4.4 m^2, while the values for the heat exchanger mode should be found at 122/19 = 6.4 m^2. The mean value between figures 3.42 and 3.43 for the collector mode is found to be 59.5 kWh/m^2 and for the heat exchanger mode it is found to be 209.5 kWh/m^2.

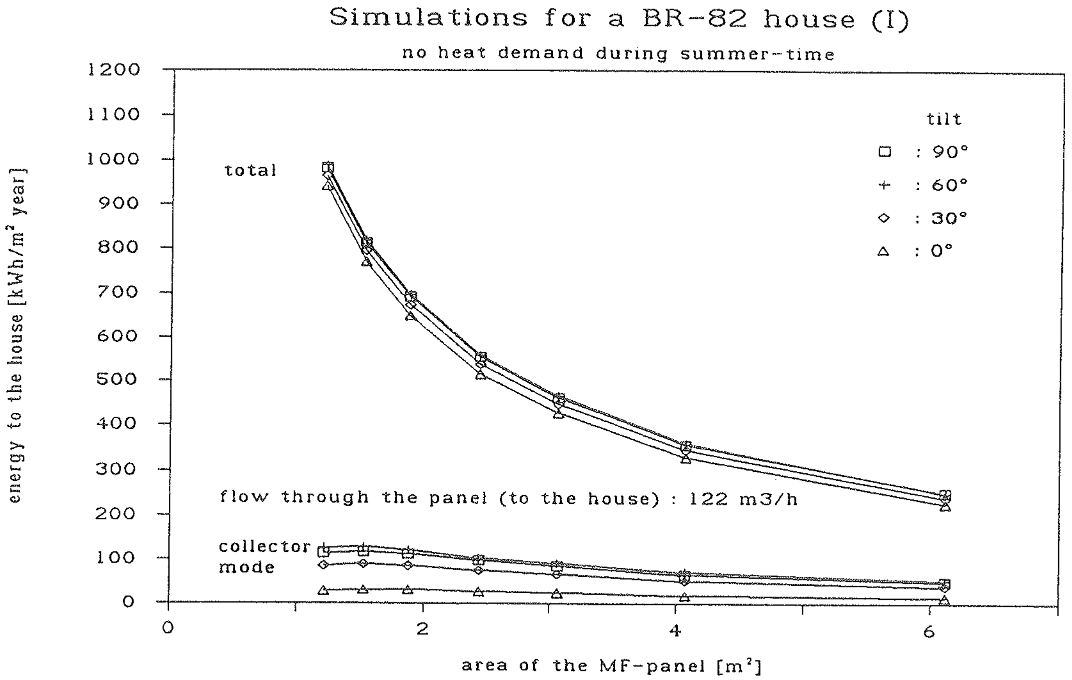

Figure 3.42. The annual performance per m² of the MF-panel installed in a BR-82 house with no heat demand during summer-time - pessimistic assumptions.

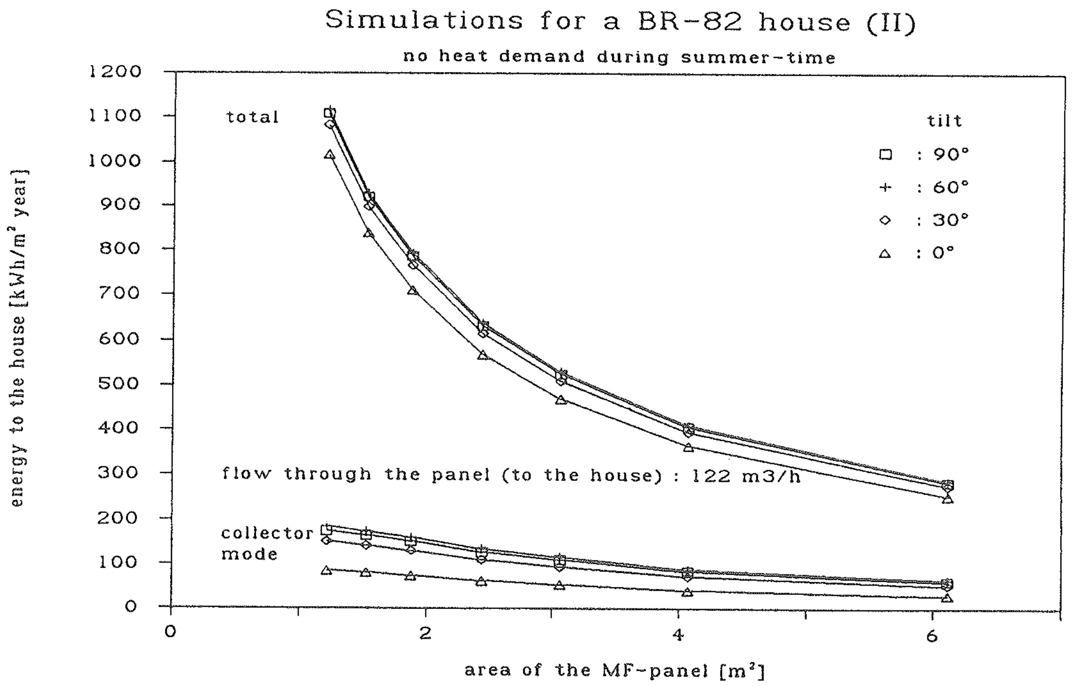

Figure 3.43. The annual performance per m² of the MF-panel installed in a BR-82 house with no heat demand during summer-time - optimistic assumptions.

The system efficiency (incl ducting) of the MF-panel is, however, as already described higher for the demonstration panel than for the prototype. The performance of the collector should thus be multiplied with 38.8/32 = 1.21, while the performance of the heat exchanger should be multiplied with 44/35.7 = 1.23. The annual performance of the MF-panel is thus:

$$59.5 \times 1.21 + 209.5 \times 1.23 = 330 \text{ kWh/m}^2$$

In (Jensen, 1990a) the reduction of the heat loss through the wall or roof due to the MF-panel was found to be 89%. With a U-value of 0.3 W/m^2K, a mean ambient temperature during the heating season of 3.3°C and an indoor temperature of 20°C, the annual reduction of the heat loss equals 23 kWh/m^2. The annual gain from the MF-panel is thus in this case:

$$330 + 23 = 353 \text{ kWh/m}^2$$

This performance is quite high compared to traditional liquid based solar heating systems for space heating purposes. However, a higher performance may be achieved if more optimal flow rates are chosen, ie a smaller area of the MF-panel for a given demand.

In (Jensen, 1990a) it was concluded that an optimal flow rate for the MF-panel in collector mode was 65 m^3/m^2h, this is also seen in figure 1.3. The performance of the MF-panel is, therefore, also found at this flow rate - also for the MF-panel in heat exchanger mode. The performance is thus found in figures 3.42-43 at an area of 122/65 = 1.88 m^2. The mean value between figures 3.42 and 3.43 for the collector mode is found to be 137 kWh/m^2, while it for the exchanger mode is found to be 602.5 kWh/m^2.

It is further assumed that the efficiencies due to the longer panel are increased by 20%. The annual performance is - again assuming no traditional heat recovery unit in the ventilation system:

$$(137 + 602.5) \times 1.2 + 23 = 910 \text{ kWh/m}^2$$

This much higher performance per m^2 is paid by a smaller solar fraction for the system as the high performance is achieved by increasing the demand on the panel.

A problem with the present MF-panel is that it is developed for covering part of the space heating demand of the building - ventilation and transmission losses. This means that much solar radiation is not utilized during summer-time with no space heating demand. In section 6 it is discussed how this solar radiation may be utilized for preheating of domestic hot water.

The above-calculated performances will be used in section 5, where the economy of the MF-panel concept is evaluated.

4. Exposed Problems

When evaluating a demonstration project it is of course important to report if the project has turned out to be as expected, however, it is even more important to report all the failures and problems which have occurred during the project, as there is often more to be learned from failures than from successes.

This section will summarize the problems exposed during the MF-panel demonstration project at Wewer's Brickyard.

4.1. The Building

The building was not ideal for the installation of the MF-panel. The building has no need for continuous mechanical ventilation, the natural infiltration rate was very high, there was after all no need for decreasing the degree of humidity within the building (as this would often disturb the production within the building), etc.

The measured performance of the MF-panel has thus been very low. However, based on the measurements it has been possible to extrapolate to a more ideal building, resulting in much higher performances - even higher performances than could be expected from the test on the prototype.

The experience from Wewer's Brickyard thus revealed that MF-panels should only be installed on buildings with a need for continuous mechanical ventilation.

4.2. The MF-panel

The MF-panel was installed on an existing roof of the building. The actual design has to be based on this. A more ideal situation would have been if the MF-panel was installed in connection with the erection of the building or in connection with a retrofitting of the roof. A more ideal design could then have been chosen, and the extra cost of the MF-panel would have been less, as described in the next section.

It would have been nice if it was possible to demolish a part of the panel in order to be able to inspect if there have been any problems with any of the materials used in the panel, as this would have given important information for future projects with the MF-panel. However, this was not possible.

Some problems have, however, been exposed for the cover of the MF-panel.

From the start the cover was fastened to the panel by means of plastic strips, which were clicked to the aluminium profiles carrying the covers, as described in section 2.2.1. This was the situation for more than two years when one of the covers was blown off in a very hard storm in the middle of January 1993. This is shown in figure 4.1. The plastic strips were then replaced with the originally intended aluminium profiles. It is, however, remarkable that only one of the covers was blown off. The cover plate was not damaged and could be placed in its original position again.

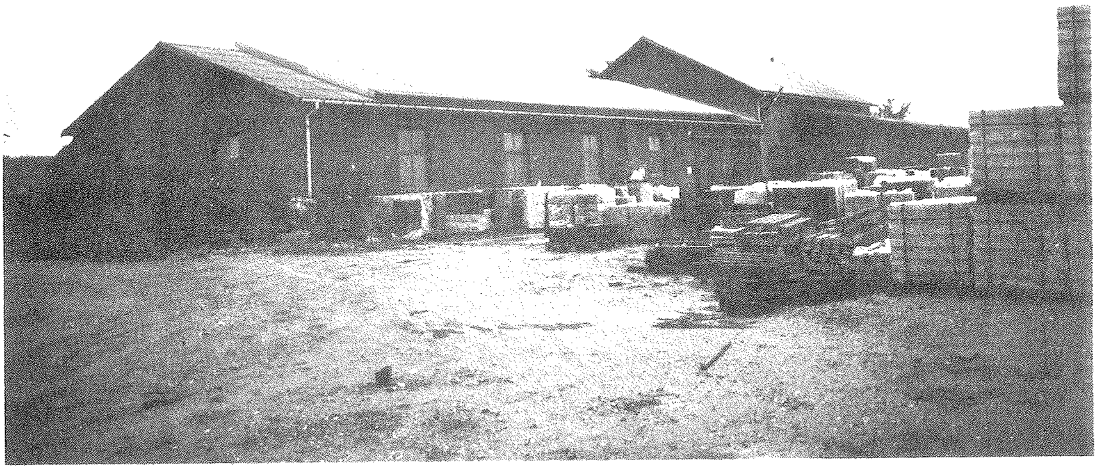

Figure 4.1. One of the cover plates blown off during a very hard storm in January 1993.

The plastic strips were replaced with an aluminium profile with sealing strips between the aluminium profiles and the cover. However, the material of the cover - polycarbonate - has a very large expansion coefficient. This means that the cover moves a lot within the profiles fastening the cover to the panel. Due to this movement of the cover, the sealing strips have many places left their initial position as seen in figure 4.2. This has most probably reduced the efficiency of the MF-panel both as solar collector and as heat exchanger as false air is sucked into the panel, thus partly bypassing the absorber. It has not been possible to determine how large the reduction is.

The cover will, due to the large expansion coefficient, get in contact with the trapezium corrugated plate, during periods with high temperature in the panel, leading to damage of the cover. For this reason spacers, as shown in figure 2.26, were located on the trapezium corrugated plate. The screws, which get in contact with the cover, are, however, also in thermal contact with the absorber. This means that the temperature of the screws also becomes very high. An inspection of the panel revealed beginning damage to the cover at the top of the panel just over the spacers. The spacers should thus not only maintain a certain distance between the cover and the absorber, but should also create a thermal insulation between the cover and the absorber.

4.3. The Ducting

The MF-panel system was installed in an existing building, and the ducting was installed in the attic of this building. The installation of the ducting was made rather difficult due to the existing rafters in the attic. This has increased the price of the ducting.

The MF-panel system was installed in a building without existing mechanical ventilation. The system has, therefore, been more expensive than if it had been installed in a more ideal building.

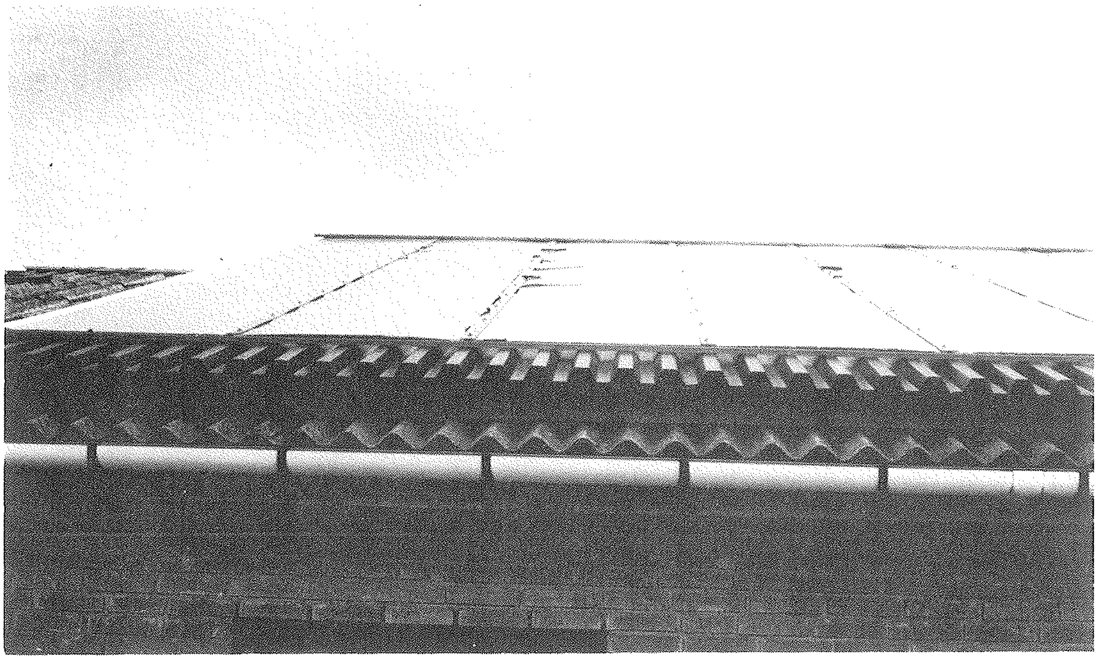

Figure 4.2. The sealing strips of the cover of the MF-panel have left their initial position.

The temperature of the MF-panel did often, as shown in section 3.1.5, reach an unacceptable temperature level - also during periods with air flow to the rooms as shown in figure 3.35. A smell of plastic was especially in the start reported by the workers of the building. The by-passes could, as discussed in section 3.1.5, not maintain the temperature level of the MF-panel at an acceptable low temperature level. It may be necessary to ventilate the MF-panel actively or to replace the cover with a cover of glass, which can resist the temperature level, has a smaller expansion coefficient and does not outgas at high temperatures.

4.4. The Controls of the System

The control of the system was not sophisticated. It consisted of a number of interconnected thermostats and hygrostats. The measurements show that the control of the MF-panel as solar collector and the opening and closing of the bypasses did function as intended. However, the system was not allowed to operate in heat exchanger mode, so the control of this and the switch between the two operation modes have not been checked.

The control system was equipped with manually operable switches for forcing the system to operate either as a solar collector or as a heat exchanger. These switches were valuable during checking and balancing of the system, and were further intended to be operated in connection with the special-purpose experiments which became necessary due to the special use of the building.

Due to hardware failure or human errors the functioning of the system was not as desired during the special-purpose experiments. The manual switches for performing the special-purpose experiments were operated by a person with insufficient knowledge about the system and the measuring system. This reveals the importance of having a person with major knowledge of the system and the measuring system operate the controls, especially during special-purpose experiments, as such a person would probably have discovered the malfunctioning of the system at the start of the test series.

4.5. The Measuring System

The measuring system has all in all been working as expected. There have not been problems with the data logger. Some sensors and the PC have, however, caused problems.

The pressure transmitters did drift a lot. The drifting was furthermore very temperature dependent. It was thus necessary to relocate the pressure transmitters from the attic to under the ceiling of room 1, and to replace one transmitter.

The DOL14 relative humidity sensors also caused problems although former experience with this sensor type is very good (Jensen et al, 1991). The intention with the DOL14 sensors was to measure the decrease in relative humidity of the rooms when the MF-panel system was in exchanger mode. As the MF-panel was not allowed to run in exchanger mode, there was really no need for the DOL14 sensors, and the calibration of the sensors was therefore stopped.

4.6. Conclusion

The above-mentioned problems arisen during the demonstration project have of course been rather annoying, but it is believed that if they are considered in further MF-projects, these projects will benefit from them.

In spite of the above-described problems, it is believed that the demonstration project has been successful, as important experience and information on the MF-concept has been gained, experience and information which could not have been obtained from the test of the prototype (Jensen, 1990a).

5. Economy

The economy of the MF-panel concept will in this section be evaluated based on the experience from the demonstration project at Wewer's Brickyard in Helsinge.

5.1. Price of the MF-panel System

The price of the actual MF-panel system at the brickyard was (in Danish kroner) as follows:

The MF-panel	150,000 DKK
The ducting	116,000 DKK
The controls	31,000 DKK
Total	297,000 DKK excl VAT

Table 5.1. The price of the actual MF-panel system at Wewer's Brickyard.

The price of the MF-panel system is thus 2360 DKK/m² excl VAT.

However, the MF-panel was installed in a building without an existing ventilation system. The MF-panel system has, therefore, been more expensive than if it was installed in a building with an existing ventilation system. The price of an MF-panel system (with the same absorber area as at Wewer's Brickyard) in a building with an existing ventilation system is estimated in the following:

The MF-panel	150,000 DKK
The ducting	20,000 DKK
The controls	30,000 DKK
Total	200,000 DKK excl VAT

Table 5.2. The price of the MF-panel system if it was installed on a building with an existing ventilation system.

The price of the MF-panel itself is identical to the price at Wewer's Brickyard. The price of the ducting system is estimated to be reduced to 20,000 DKK as only the connection between the MF-panel and the existing ducting system should be contained in the price of the MF-panel system. The price for the controls is maintained at the same level as at the brickyard. At the brickyard the price of the controls also included the connection of the fans to the electric grid. This should not be included in the here estimated price of the MF-panel system. On the other hand a more sophisticated control system may be necessary eg by combining it with the control system for the ventilation and heating system of the building.

The price of the MF-panel system is in this case 1590 DKK/m² excl VAT.

If the MF-panel was installed in connection with a retrofit of an existing roof, the extra cost of the MF-panel will be lower as the traditional roof may be saved. The wooden skeleton between the existing roof and the conchip plates - shown in figure 2.8 - may also be saved. The savings will (based on (V&S priser, 1993)) in this case be:

Corrugated fibre cement roofing	190 DKK/m^2
Wooden framework	60 DKK/m^2
Total	250 DKK/m^2 excl VAT

Table 5.3. The savings if the MF-panel system is installed in connection with a retrofit of the existing roof.

If the MF-panel substitutes a tile roof, the savings would be higher. However, when integrating the MF-panel into the roof it is necessary to make a connection between the roof and the cover of the MF-panel in order to prevent rain from getting in. It is estimated that the cost of such a connection (flashing) will be 150 DKK/m^2.

The price of the MF-panel system will in this case be 1490 DKK/m^2 excl VAT.

If the MF-panel was installed at the same time as the erection of the building and the MF-panel was applied on an insulated roof the savings are, based on (V&S priser, 1993), estimated to be:

Corrugated fibre cement roofing	190 DKK/m^2
Insulation	65 DKK/m^2
Conchip	75 DKK/m^2
Wooden framework	60 DKK/m^2
Total	390 DKK/m^2 excl VAT

Table 5.4. The savings if the MF-panel system is installed in connection with the erection of the building.

If the MF-panel is installed during the erection of the building, the integration of the panel may be designed in such a way, that the cost of the flashing may be lower than assumed in the former case. It is, however, also assumed here, that the price of the flashing is 150 DKK/m^2. The MF-panel may in a new building substitute the traditional heat recovery unit in the ventilation system. The price of this unit may then be subtracted from the price of the MF-panel system. This will, however, not be done here.

The price of the MF-panel system will, therefore, in this case be 1350 DKK/m^2 excl VAT.

5.2. Payback Time for the MF-panel System

The payback time for the MF-panel system will in the following be evaluated for five cases. The five cases are:

1: The actual case from Wewer's Brickyard: Annual performance of the system from section 3.1.1. - 96 kWh/m². It is assumed that the fans use an amount of electricity which equals 5% of the performance of the MF-panel system as found in section 3.1.6.

2: The actual case from Wewer's Brickyard, but where the system is also allowed to act as a heat exchanger: Annual performance of the system from section 3.2. - 353 kWh/m². The electricity demand for the fans is also here assumed to be 5% of the performance of the MF-panel system.

3: The MF-panel installed in a more ideal building and with a more optimal flow rate of air through the panel: Annual performance of the system from section 3.2. - 910 kWh/m². The building has already a ventilation system, so the electricity demand of the fans does not constitute a charge on the economy of the MF-panel. There is no traditional heat recovery unit in the ventilation system.

4: As 3, but where the MF-panel is installed as a part of a retrofit of the existing roof.

5: As 3, but where the MF-panel is installed at the erection of the building.

The price of the MF-panel system for the five above-described cases is given in the previous section. However, solar heating systems are subsidized in Denmark. The subsidies are 5 DKK/kWh yearly performance, but with a maximum of 30% of the installation cost. For case 2-3 the subsidies are 30%.

The energy demand for space heating in the workshop at Wewer's Brickyard is covered by a gas fired boiler. The payback time is in the following calculated based on the price of natural gas in Denmark. The payback time is further calculated both for industrial buildings and for residential buildings, the latter representing buildings where VAT and taxes cannot be deducted from the energy price. The gas prices and the prices of electricity were - from (VVS, 1992-93):

	industry	residential	
gas price	0.13	0.42	DKK/kWh
electricity	0.454	0.924	DKK/kWh

Table 5.5. Actual energy prices during the heating season 1992-93.

It is assumed that the efficiency of the gas boiler is, as at the brickyard, 0.93. Taking this into consideration the above-mentioned prices are:

	industry	residential	
gas price	0.144	0.45	DKK/kWh

Table 5.6. The energy (gas) price when considering the efficiency of the gas boiler.

The payback time used here is the simple payback time, ie the investment divided by the yearly savings. This gives for the five cases, when it is considered, that the price of the MF-panel in residential buildings should include VAT:

	industry	residential	
case 1	162	61	years
case 2	39	15	years
case 3	8.5	3.4	years
case 4	7.9	3.2	years
case 5	7.2	2.9	years

Table 5.7. The simple payback time for an MF-panel system considering the above-mentioned cases.

The evaluation of the payback time reveals, what was already known, that the actual MF-panel system at Wewer's Brickyard is not profitable.

It is shown, that the system should be installed on buildings with continuously running ventilation systems. It is, however, not important that the system is installed in connection with a retrofit of the building or the erection of the building.

The investigation further shows, that the MF-panel system is most profitable in residential buildings. This is because the industry can deduct VAT and tax on energy. However, with the introduction of more and more green taxes - also for the industry - the MF-panel system will become more and more profitable.

The MF-panel seems to be profitable on residential buildings even without subsidies and green taxes.

The economy of the MF-panel system would be even better if the panel was allowed to pre-heat domestic hot water, because the MF-panel system, as installed at Wewer's Brickyard, does not utilize the large amount of solar radiation occurring during the summer-time. Such an extension of the multi-function concept of the MF-panel will be discussed in the next section.

When installing an MF-panel system, the cost of a traditional heat recovery unit may in some cases be subtracted from the price of the MF-panel system. This has not been considered here. However, when considering installation of an MF-panel system on an actual building the cost and performance of the MF-panel system should be compared with the cost and performance of a system with a traditional heat recovery unit.

6. Further Developments

The good results from the preliminary analysis of the first measurements (Jensen, 1992), also described in section 3.1.2, encouraged the group behind the MF-panel concept to further investigate the possibilities of the concept. This was done in two different ways: Firstly a further development of the concept and secondly a search for industrial partners for a commercialization of the concept.

In 1992 an application to the CEC financed demonstration program THERMIE was submitted. The aim was to demonstrate a further developed concept of the MF-panel called Integrated Energy Producing Building Component. This concept comprises, besides the features of the original MF-panel, an integration of PV-elements in the cover of the component and utilization of the solar radiation especially during the summer-time for preheating of domestic hot water. The technical annex of this application is included as appendix D in the present report.

The project did unfortunately not obtain funding, maybe because the project contained too much research. The project was, therefore, redefined as a proposal for the CEC financed research programme JOULE II. This project did not obtain funding either. The official explanation was that there were too many applications for too little funding.

Finally an application was submitted to the research and development programme for renewable energy financed by the Danish Ministry of Energy. This project was less ambitious than the JOULE II proposal as it only concerned the integration of a liquid based absorber in the MF-panel, so that the solar radiation during summer-time may also be utilized.

This latter project did obtain funding and was successfully finalized at the beginning of 1994 (Jensen, 1994). A concept with a liquid based absorber located between the cover and the trapezium corrugated plate has been developed - both in terms of small and large modules. The concept is called MF/AW-panel (AW standing for air/water). A prototype has been tested in the artificial sun at the Thermal Insulation Laboratory, Technical University of Denmark. The test revealed, that the performance of the MF/AW-panel as liquid based solar collector is as high as other solar collectors on the Danish market, while the performance of the panel as air collector did not decrease compared to the MF-panel. The test further shows, that the performance of the panel increases when acting both as a liquid and an air collector. This is, however, not surprising as the mean temperature of the panel is lower than in traditional collectors leading to a smaller heat loss and thereby to increased efficiency. Principles for the integration of the MF/AW-panel in buildings have further been developed.

Based on the test of the MF/AW-panel it is estimated that the yearly performance of the MF/AW-panel will be 200-400 kWh/m^2 higher than the yearly performance of the MF-panel. This higher performance is due to preheating of domestic hot water. How much higher the performance is, is dependent on the actual hot water demand of the building, where the MF/AW-panel is installed.

At the same time effort was spent on introducing the concept to the industry. Several major Danish companies in the building industry have been contacted and meetings have been arranged. However, due to the stagnation in the building industry no company wished to start a production of the MF-panel at the present time.

The industry was not only contacted directly, an article was also published in a major Danish magazine for the building industry (Jensen, 1993) inviting investors to join the group behind the MF-panel.

A contribution was further sent to a competition arranged by the Finnish plastic manufacturer Neste. A part of the contribution was the poster shown in figure 6.1. The aim of the contribution was not to win the competition, but again to invite the industry.

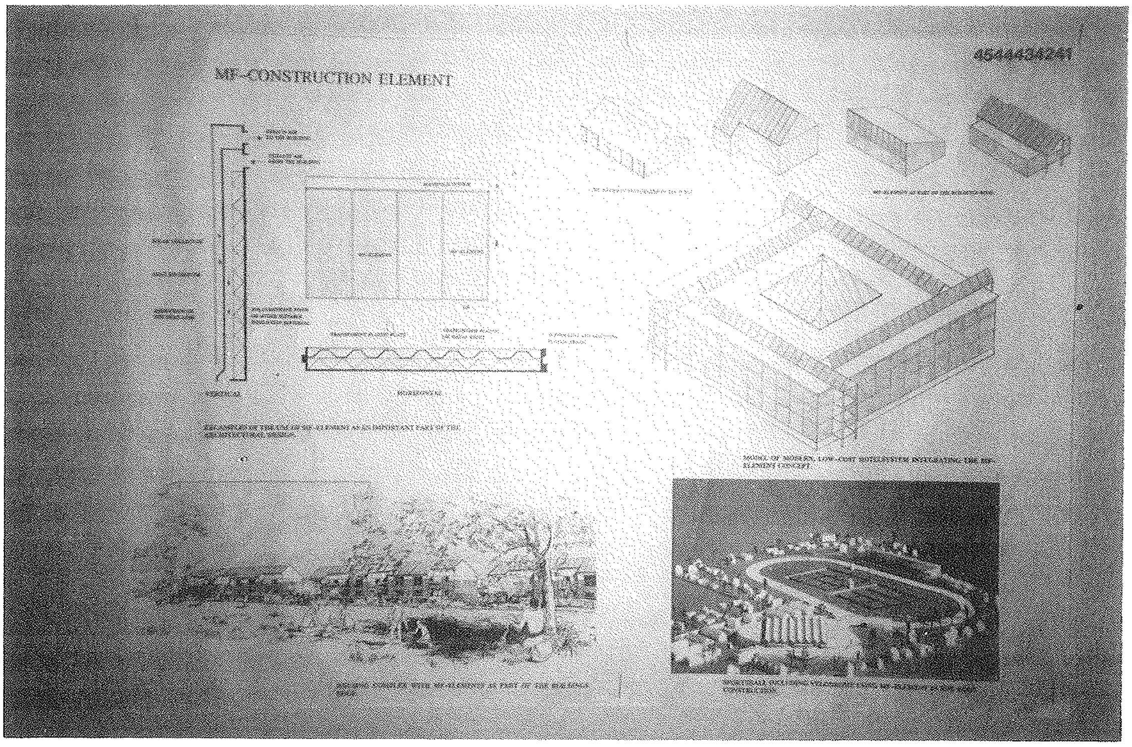

Figure 6.1. The poster of the contribution to the competition arranged by Neste.

In spite of all this no manufacturer has as yet been interested in investing in a production of the MF-panel. However, it seems now that the stagnation in the building industry is beginning to lighten, and based on the very promising result from the present project and the project described in (Jensen, 1994) the group behind the MF-panel is determined to carry on, and is now looking for suitable buildings where the MF/AW-panel may be demonstrated.

7. Conclusions

The MF-panel concept has been demonstrated on a workshop at Wewer's Brickyard in Helsinge, Denmark. The idea was originally to install the MF-panel system in connection with the erection of a larger shopping and conference centre. However, due to different problems, this idea had to be given up. The building at the brickyard was as explained not ideal for the purpose of demonstrating the MF-panel system, but it was judged that it was good enough for obtaining important information on the concept. However, during the installation of the MF-panel system the building became, due to changes in the production within the building, less suitable as demonstration building. However, at that time it was too late to change the plans.

126 m² of MF-panels were installed on the south facing roof of the workshop. The building was equipped with a new ventilation system connecting the MF-panel with the rooms of the workshop. A comprehensive measuring system was installed in the workshop in order to obtain detailed information on the performance of the MF-panel system.

The installation of the system and the following measuring period revealed much important information on good and bad things about the actual MF-panel system which, when considered in future MF-panel systems, may lead to better systems.

The measurements showed that the performance of the MF-panel system is higher than what could be expected based on the experience from the test of the prototype of the MF-panel. The MF-panel at the demonstration project was longer than the prototype. This may explain a part but not all of the increase in performance.

Both the performance of the MF-panel as solar collector and as heat exchanger is higher than expected. The mean system efficiency of the MF-panel acting as solar collector was measured to be approximately 39%, while the system efficiency of the MF-panel acting as heat exchanger was measured to be 44%. The flow rates through the MF-panel was not optimal - it was quite low. This influences especially the efficiency of the MF-panel as solar collector. The efficiency of the MF-panel as solar collector would have been considerably higher if a more optimal flow rate was applied, while the efficiency of the MF-panel as heat exchanger is almost independent on the flow rate, but very dependent on the temperature difference between the room temperature and the ambient temperature.

The measurements show that the three bypasses, installed for cooling the MF-panel during summer-time with the fans switched of, did not cool the system as intended. It is, therefore, important to investigate this further. The panel should either only contain materials which may withstand the high temperatures or the MF-panel should be cooled actively by use of fans. The former solution is to be preferred as the latter requires energy for running the fans.

The electricity consumption of the fans in the actual system was only about 5% of the performance of the MF-panel system. However, the MF-panel should only be installed in buildings with a demand for continuous mechanical ventilation. The fans in such a system will be running anyway, so their electricity demand will not constitute a charge on the economy of the MF-panel system.

The performance of the MF-panel for the heating season 1992-93 was measured to be 96 kWh/m² per year. This very low performance was caused by the fact that it was not possible to run the MF-panel system as heat exchanger between fresh air to the building and exhaust air from the building, as this could have disturbed several special-purpose productions within the workshop. If, however, the MF-panel system had operated as intended with the actual low flow rates, the yearly performance would have been 353 kWh/m^2. This is higher than for many liquid based solar heating systems especially systems for combined preheating of domestic hot water and space heating.

If the MF-panel system was installed in a more ideal building and with a more optimal flow rate of air through the panel, the yearly performance of the MF-panel system would have been 910 kWh/m^2. This high performance could be even higher, if the MF-panel system was also allowed to preheat domestic hot water especially during the summer-time, where the MF-panel would otherwise be switched off as there is no demand for space heating and preheating of ventilation air. An MF-panel concept with an integrated liquid based absorber for preheating of domestic hot water has, based on the experience from the demonstration project, been developed in a project financed by the Danish Ministry of Energy. This project shows, that the performance of the MF-panel may be increased with 200-400 kWh/m^2 per year dependent on the demand for domestic hot water.

The economic evaluation of the MF-panel concept shows that installed in buildings with a continuous demand for mechanical ventilation, the simple payback time for the MF-panel system would be below 4 years in residential buildings while the payback time in industrial buildings would be around 8 years. The longer payback time for industrial buildings is due to the fact, that the industry can deduct VAT and tax on energy. However, with the increasing interest in green taxes - also for the industry - the above-mentioned rather low payback time will become even lower.

The good results from the demonstration project have encouraged the group behind the MF-panel system to further develop the concept and to get the industry interested in producing the system. The MF-panel system has been developed further. The MF/AW-panel, including a liquid based absorber for preheating of domestic hot water, has been developed and further developments are being considered. The industry has been invited either directly or indirectly; however, due to the stagnation in the building industry no manufacturer has yet wished to produce the element. The group behind the concept is, however, determined to carry on and is for the time being looking for a suitable building for demonstrating the MF/AW-panel concept.

8. References

The Danish Ministry of Housing, 1983. Building Regulations 1982. Publication no. 66.

Jensen, S.Ø., 1990a. Results from tests on a Multi-Function Solar Energy Panel. The Thermal Insulation Laboratory, Technical University of Denmark. ISSN 0905-1511 Report no 213.

Jensen, S.Ø., 1990b. Multi-Function Solar Energy Panel. In proceedings from the symposium "Building Physics in the Nordic Countries", Trondheim, Norway, August 20-22,1990. pp 159-164.

Jensen et al, 1991. PASSYS - Danish participation, Annual report 1990. Thermal Insulation Laboratory, Technical University of Denmark. Report no 91-11.

Jensen, S.Ø., 1992. Status Report - MF-demonstration project at Wewers Brickyard in Helsinge, May 1992. Thermal Insulation Laboratory, Technical University of Denmark. Report no 92-12.

Jensen, S.Ø., 1993. Taget som solfanger - The roof as a solar collector (in Danish). Byggeindustrien - Special '93. pp 60-62.

Jensen, S.Ø., 1994. Development of the MF/AW-panel.

Lawaetz, H. and Jørgensen, L.S., 1977. Videnbank - 3 huses opvarmningsbehov. Knowledge base - the heat demand of three houses (in Danish). Thermal Insulation Laboratory, Technical University of Denmark.

Statens Byggeforskningsinstitut, 1982. Weather Data for HVAC and energy - Danish Test Reference Year. SBI Report no 135.

V&S priser, 1993. Husbygning - Brutto - Prices for building construction (In Danish). V&S Byggedata A/S.

VVS, 1992-93. VVS - magazine for heating, ventilation, sanitary applications, environment and energy technology (in Danish). Teknisk Forlag A/S.

Appendix A

Paper to the symposium "Building Physics in the Nordic Countries"
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MULTI-FUNCTION SOLAR ENERGY PANEL

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1. INTRODUCTION

The present paper deals with the experience and conclusions gained from tests carried out on two prototypes of a Multi-Function solar energy panel (ØSTERGAARD JENSEN, 1990). Besides being the wall (or the roof) of a house the panels investigated 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 Multi-Function solar energy panels operating only as solar collectors or only as heat exchangers, has been measured for different flows through the panels. On the basis of the measured efficiencies, simulations have been carried out 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 the influence of condensation in the panel and to find the reduction of the heat loss compared to a normal wall.

2. DESIGN OF THE MULTI-FUNCTION SOLAR ENERGY PANEL

A Multi-Function solar energy panel is constructed to adapt a facade often used for industrial buildings, a facade with corrugated metal profiles, to serve 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 trapezium corrugated metal sheet. The two plates are mounted in front of a normal insulated outer wall. At the top (and maybe at the bottom) of the panel there are box-shaped manifolds - see figure 1. In this way it is possible to let in air through the manifolds into the two sets of air gaps formed on either side of the trapezium corrugated metal sheet. The panel can thus 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 corrugated metal sheet 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.

The Multi-Function solar energy panel can serve different purposes:

1) Traditional air based solar collector,
2) Heat exchanger and solar collector for preheating of fresh air,
3) Heat exchanger and solar collector for preheating of air to the condenser of a heat pump.

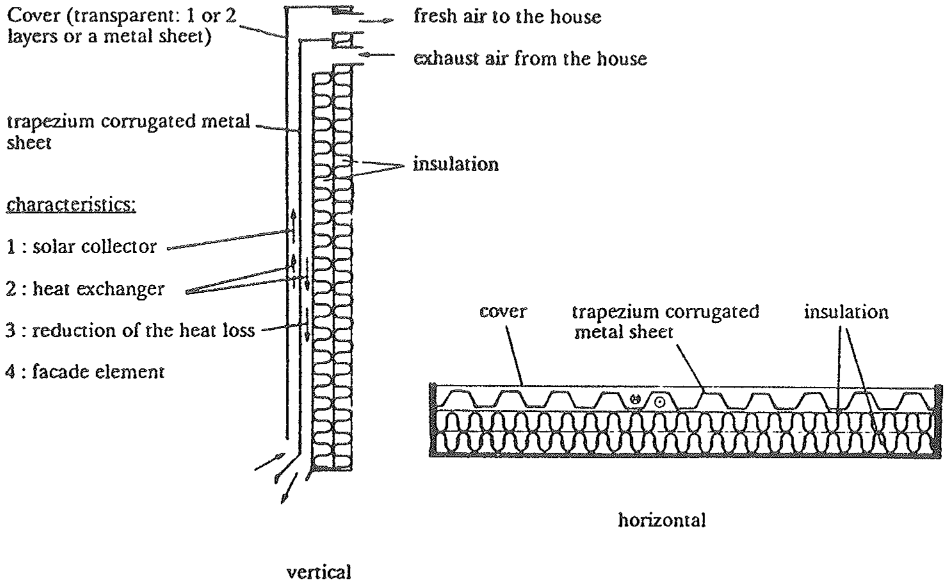

Figure 1. Outline of a Multi-Function solar energy panel serving as pre-heater of fresh air.

The work reported here deals with the Multi-Function solar energy panel serving as a solar collector and a heat exchanger for preheating of fresh air.

Two prototypes of the Multi-Function solar energy panels with different covers have been tested. The covers were:

1) a 1 mm steel plate painted mat black and
2) a 10 mm double-walled, ribbed polycarbonate plate.

3. TEST OF THE TWO PROTOTYPES OF THE MULTI-FUNCTION SOLAR ENERGY PANELS

The two prototypes of the Multi-Function solar energy panel have been tested when only working as solar collectors or as heat exchangers between exhaust air from and fresh air to the house.

3.1. Test of the Multi-Function solar energy panels as solar collectors

The efficiency of the two Multi-Function solar energy panels working only as solar collectors for preheating of fresh air has been measured usir^ the artificial sun at the Thermal Insulation Laboratory. The Multi-Function solar energy panels were connected to a ventilator via a flexible duct. The flow through the panels was varied from 30-170 m^3/m^2h (the flow in traditional air based solar collectors is normally between 30 and 100 m^3/m^2h). The prototypes have further been tested with and without the influence of wind. When wind was simulated, an air stream of about 2 m/s was created along the cover of the panels. The results from the tests are shown in figure 2.

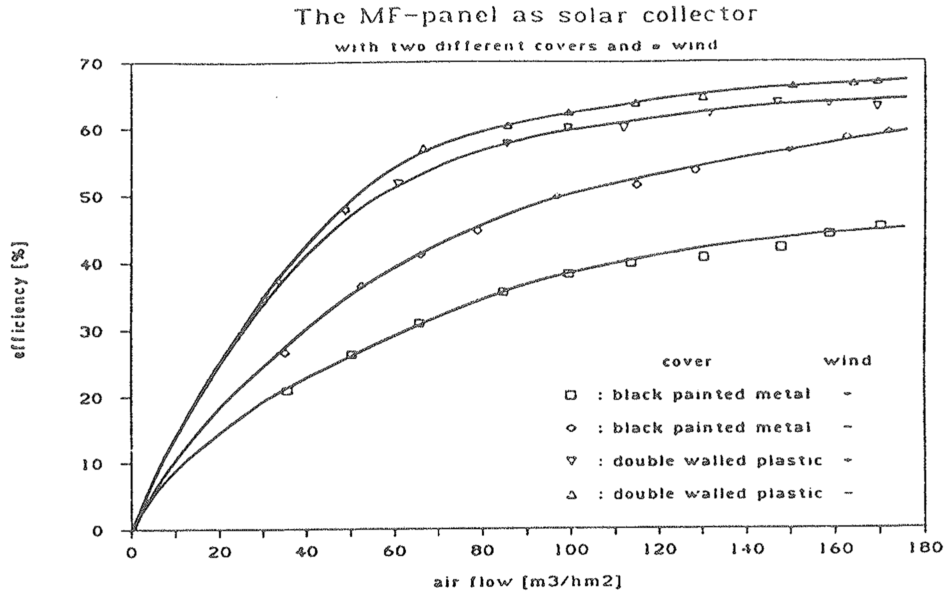

Figure 2. The results from tests made on the Multi-Function solar energy panels working only as solar collectors for preheating of fresh air.

The high efficiency of the panels when working as solar collectors is due to the fact that the inlet to the panels is ambient air. The figure further shows that the efficiency increases and the influence of wind decreases when a transparent cover is used instead of a metal sheet.

3.2. Test of the Multi-Function solar energy panels as heat exchangers

The efficiency of the Multi-Function solar energy panels when working only as heat exchangers between exhaust air and fresh air to the house has been measured by installing the panels in a gate of an experimental building. The tests showed that the efficiency of the Multi-Function solar energy panels working as heat exchangers is about 30%. 28% at a flow rate of fresh air of 180 m^3/m^2h and 34% at a flow rate of 30 m^3/m^2h. The efficiency is quite large compared to the rather small heat transferring area between the two air streams. The efficiency is independent of the type of cover of the Multi-Function solar energy panel, at least when the panel is mounted vertically.

4. ANNUAL PERFORMANCE OF THE MULTI-FUNCTION SOLAR ENERGY PANEL

In the previous paragraph the efficiency of the Multi-Function solar energy panel when working either as a solar collector or as a heat exchanger is given. This, however, does not give an impression of the performance of a Multi-Function solar energy panel installed in a real building. Simulations have, therefore, been carried out using the measured efficiencies for the panel with the transparent cover as input data. The Danish Test Reference Year has been used as weather data. An annual net space heating demand of 14,100 kWh, matching a house with a built-up area of 140 m^2, insulated according to the Danish Building Regulations, is one of the energy demands used in the simulations.

When the 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 Multi-Function solar energy 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 Multi-Function solar energy panel. In the pessimistic series it is assumed that the panel only works 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 Multi-Function solar energy panel, and when the solar input is small the solar input is not considered.

The difference in overall performance for the two series of simulations is, however, only between 8 and 15%. Figure 3 and 4 show a small selection of the results of the performed simulations. The figures show the total energy output and the output of solar energy from the Multi-Function solar energy panel under the optimistic assumptions. The figures show the output under different conditions: Area of the panel (and thereby flow through the panel. The total air flow through the panel is equal to the ventilation of the house = 0.4 air changes per hour), tilt and orientation. In ØSTERGAARD JENSEN (1990) many simulations have been performed with different heat demands of the building and different orientations of the Multi-Function solar energy panel.

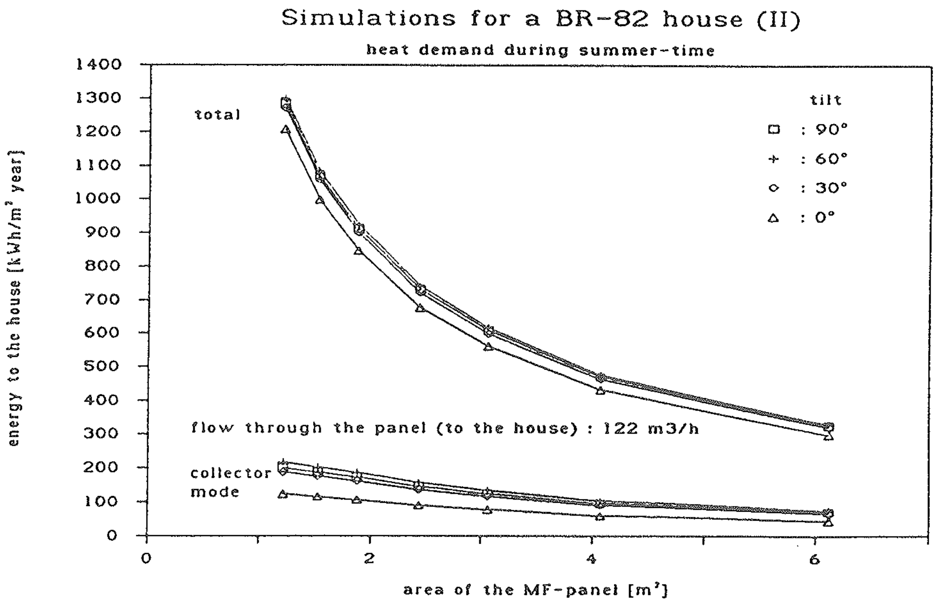

Figure 3. The annual performance per m² of a south facing Multi-Function solar energy panel in a 140 m² house insulated according to the Danish standards.

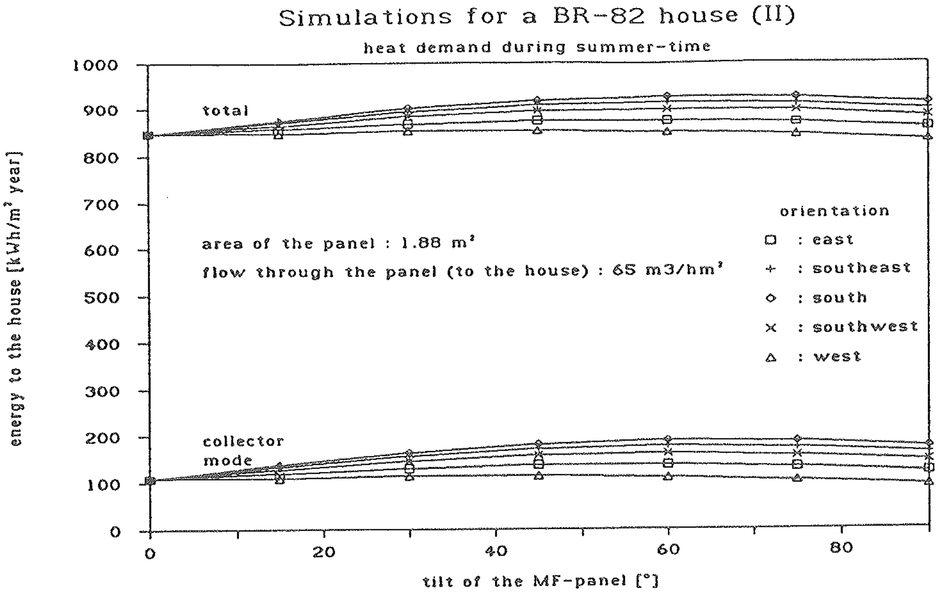

Figure 4. The annual performance per m2 of a Multi-Function solar energy panel with a flow rate of 65 m^3/m^2h in a 140 m^2 house insulated according to the Danish standards.

The simulations show that a Multi-Function solar energy panel can cover 23-44% of the heat loss due to ventilation of a house. The simulations also show that the main heat gain is received when the Multi-Function solar energy panel is working as a heat exchanger, the energy gain from the sun is between 3 and 25% of the total output from the Multi-Function solar energy panel - highest for large areas of the Multi-Function solar energy panel. The total output from the panel is rather independent on the tilt and orientation of the panel. The total output from the panel is between 250 and 1350 kWh/m^2year depending on the flow per m^2.

5. CONDENSATION IN THE MULTI-FUNCTION SOLAR ENERGY PANEL

Preliminary calculations have been performed in order to determine the effect of condensation in the Multi-Function solar energy panel. Condensation may occur due to the heat exchange between the warm, humid exhaust air and the cold fresh air. The investigation showed that when installed in residential buildings condensations will not occur, because the relative humidity of the exhaust air normally is around 60% and the temperature of the fresh air seldom gets below -10 °C. If, however, condensation occurs eg if installed in industrial buildings with a relative humidity of the exhaust air close to 100%, the energy output can easily be a half time higher than if no condensation occurs.

6. DECREASE OF THE HEAT LOSS THROUGH THE WALL

The heat loss through the insulated wall of a Multi-Function solar energy panel will be decreased because the warm exhaust air is led down along the outer surface of this wall. A small example will show this: The U-value of the insulated wall of the prototypes of the Multi-Function solar energy panel is calculated to be 0.41 W/m^2K. According to the Danish Building Regulations the U-value for such a lightweight wall should be 0.3 W/m^2K. If the ambient temperature is -12 °C and the indoor temperature is 20 °C (a normal Danish design case) then the heat loss through the insulated wall of the Multi-Function solar energy panel will be 11% of the heat loss through the wall specified by the Danish Building Regulations although the latter has a lower U-value.

7. CONCLUSION

By Multi-Function solar energy panels a very simple concept (with many applications) for gaining energy has been developed. When working as a solar collector the efficiency of the panel is between 30 and 60% for flow rates between 30 and 100 m^3/m^2h. The efficiency of the panel working as a heat exchanger between fresh air and exhaust air is around 30%. Installed in a residential building the output is between 250 and 1350 kWh/m^2year, mainly dependent on the area of the panel. The panel can thus cover 23-44% of the energy loss due to ventilation of the house. Due to the warm air stream down along the outer surface of the insulated wall the heat loss through this is decreased - for a normal Danish design case the heat loss is decreased to one fifth of the heat loss through a Danish standard wall.

Preliminary economical calculations have shown that the price of a Multi-Function solar energy panel should be half the price of a traditional heat exchanger for heat recovery in ventilation systems in order to be profitable. This should be possible to obtain especially in connection with erection of new buildings as the only things missing when going from a wall or roof to a Multi-Function solar energy panel are the outer cover and the manifolds.

A demonstration project with up to 200 m^2 Multi-Function solar energy panels on the roof of a builing in a brickyard is expected to be started during 1990.

8. ACKNOWLEDGEMENTS

The Multi-Function solar energy panel is based on an idea by the Danish architect Arne Meldgaard and is developed in a cooperation between the Thermal Insulation Laboratory, the Architects Arne Meldgaard and Techline International Energy Systems. The work has been financed by the Danish Ministry of Energy.

9. REFERENCES

ØSTERGAARD JENSEN S. (1990) Results from tests on a Multi-Function Solar Energy Panel. Thermal Insulation Laboratory, Technical University of Denmark. Report no. 211. 80 pages.

Appendix B

Measuring card no 1

Slot no.	Sensor name	Location of the sensor
1	irradiation	pyranometer on the roof to the left of the MF-panel
2	room temp 1	thermocouple at the thermostat and the pressostat in room 1
3	RH1	DOL14-sensor at the thermostat and the pressostat in room 1
4	1-in	thermocouple in the inlet to room 1
5	2-in	thermocouple in the inlet to room 1
6	3-in	thermocouple in the inlet to room 1 = thermocouple just after the orifice in duct 3-in
7	1-out	thermocouple in the outlet from room 1
8	2-out	thermocouple in the outlet from room 1
9	3-out	thermocouple in the outlet from room 1
10	3-MF-out mean	mean value of 7 thermocouples just before the outlet of duct 3-out to the MF-panel
11	3-MF-in mean	mean value of 7 thermocouples just after the inlet from the MF-panel to duct 3-in
12	3-in mean before fan	mean value of 7 thermocouples just before the fan in duct 3-in
13	3-in mean after fan	mean value of 7 thermocouples just after the fan in duct 3-in
14	pressure drop over the orifice 3-in and 3-out	pressure transducer no. 2922 connected to the orifices in duct 3-in and 3-out
15	temp after orifice 9-in	thermocouple just after the orifice in duct 9-in
16	temp after orifice 3-out	thermocouple just after the orifice in duct 3-out
17	11	thermocouple in the collector part of the MF-panel - 1.2 m from the bottom
18	12	thermocouple in the collector part of the MF-panel - 2.4 m from the bottom
19	13	thermocouple in the collector part of the MF-panel - 3.6 m from the bottom
20	14	thermocouple in the collector part of the MF-panel - 4.8 m from the bottom

Measuring card no 2

Slot no	Sensor name	Location of the sensor
1	ambient temp	shielded thermocouple at the north side of the building
2	ambient RH	shielded DOL14-sensor at the north side of the building
3	21	thermocouple in the outgoing part of the MF-panel - 1.2 m from the bottom
4	22	thermocouple in the outgoing part of the MF-panel - 2.4 m from the bottom
5	23	thermocouple in the outgoing part of the MF-panel - 3.6 m from the bottom
6	24	thermocouple in the outgoing part of the MF-panel - 4.8 m from the bottom
7	4-in	thermocouple in the inlet to room 1
8	4-out	thermocouple in the outlet from room 1
9	room temp 2	thermocouple at the thermostat and the pressostat in room 2
10	RH2	DOL14-sensor at the thermostat and the pressostat in room 2
11	5-8-out1	thermocouple in the outlet from room 2
12	5-8-out2	thermocouple in the outlet from room 2
13	5-8-in1	thermocouple in the inlet to room 2
14	5-8-in2	thermocouple in the inlet to room 2
15	pressure drop over the orifice 5-8-in and 5-8-out	pressure transducer no. 3612 connected to the orifices in duct 5-8-in and 5-8-out
16	temp after orifice 5-8-in	thermocouple just after the orifice in duct 5-8-in
17	temp after orifice 5-8-out	thermocouple just after the orifice in duct 5-8-out
18	room temp 3	thermocouple at the thermostat in room 3
19	9-in	thermocouple in the inlet to room 3
20	pressure drop over the orifice 9-in	pressure transducer no. 3613 connected to the orifices in duct 9-in

Measuring card no 3

Slot no	Sensor name	Location of the sensor
1	hour counter - gas	at the gas boiler
2	hour counter - by-pass	at the hour counter at the attic
3	pressure drop - 3-in	connected to the valves for pressure transmitter no 2922
4	pressure drop - 3-out	connected to the valves for pressure transmitter no 2922
5	pressure drop - 5-8-in	connected to the valves for pressure transmitter no 3612
6	pressure drop - 5-8-out	connected to the valves for pressure transmitter no 3612
7	indication of solar heat to room 1	in the poster
8	indication of heat exchange for room 1	in the poster
9	indication of solar heat to room 2	in the poster
10	indication of heat exchange for room 2	in the poster
11	indication of solar heat to room 3 + text	in the poster
12	text to slot no 7	in the poster
13	text to slot no 8	in the poster
14	text to slot no 9	in the poster
15	text to slot no 10	in the poster
16	indication if the data acquisition system is running	in the door of the cabinet containing the data acquisition system
17		
18		
19		
20		

Appendix C

Measuring program for the measuring system at Wewer's Brickyard

```
10 '**************************************************
20 ' THIS PROGRAM CONTROLS A SOLARTRON DATA ACQUISITION
30 ' SYSTEM FOR A CEC SUPPORTED DEMONSTRATION
31 ' PROJECT WITH MULTI-FUNCTION SOLAR ENERGY PANELS
40 ' DATE: MARCH 1992
50 ' BY  : SØREN ØSTERGAARD JENSEN
60 ' DSN : MF-MEAS (VERSION 8)
70 '************************************************
80 '
100 CLEAR, &HF000
105 DRIVERADDRESS% = &HF000
110 '
130 DIM RESULT1(20),RESULT2(20),RESULT3(20),RESULT4(20),RESULT5(20),STYR%(3),M(70),S(70),MEAS(20),STATUS-
%(20),RO(5),N%(70),ATTACHED%(30)
135 '
219 GOSUB 8000
220 CLS
310 IPAS%=0
500 '------------------------------------------
501 '           START LOOP
502 '------------------------------------------
503 CLS
510 GOSUB 1200
600 GOSUB 1000
650 IF STYR%(1)=2 THEN GOTO 1500
700 IF TIDSCANNEW>TIDL THEN GOTO 990
710 GOSUB 4000
711 GOSUB 4400
712 GOSUB 7720
715 GOSUB 4500
717 GOSUB 5000
718 GOSUB 7300
719 GOSUB 7400
720 GOSUB 5400
721 GOSUB 6300
722 GOSUB 7510
723 GOSUB 3000
725 GOSUB 6000
740 IF TIDDISKNEW>TIDL THEN GOTO 990
755 GOSUB 2000
990 GOSUB 1260
999 GOTO 600
1000 '------------------------------------------
1001 '              READ WATCH
1002 '------------------------------------------
1111 HOUR%=VAL(MID$(TIME$,1,2))
1112 MIN%=VAL(MID$(TIME$,4,2))
1113 SEC%=VAL(MID$(TIME$,7,2))
1115 SEK=HOUR%*3600+MIN%*60+SEC%
1117 IF IPAS%=1 THEN GOTO 1124
1123    SEKOLD=0:TIDL=0:DAY$=MID$(DATE$,4,2)
1124 TIDL=TIDL+SEK-SEKOLD
1125 IF MID$(DATE$,4,2)=DAY$ THEN 1131
1127    TIDL=TIDL+24*60*60
1129    DAY$=MID$(DATE$,4,2)
1131 SEKOLD=SEK
1140 IF MID$(TIME$,8,1)=SEC$ THEN 1131
1150 LOCATE 20,1
1155 PRINT "               ------------------------------------------------"
1160 PRINT "               DATE: ";DATE$;"  TIME: ";TIME$;"               "
1162 LOCATE 23,1
1165 PRINT "               ------------------------------------------------"
1170 SEC$=MID$(TIME$,8,1)
1180 IPAS%=1
1190 RETURN
1200 '------------------------------------------
1201 '              KEY BOARD INTERRUPT
1202 '------------------------------------------
1210 LOCATE 1,1
1220 PRINT "               -----------------------------------------------"
1230 PRINT "                S =>  STOP"
1240 PRINT "                M =>  TEST MEASURING CARD"
1250 PRINT "                I =>  TEST I/O CARD"
1260 CHAR$=INKEY$
```

```
27( IF :H/ $= ;" HE G( ) '9(
28( IF :H/ $= I" HE G( ) .0(
29( IF :H/ $= " HE G( ) 0(
30( RE IRI
30( '- --- -- --- -- -- -- -- --- -- -
31( ' ANI L :ST OF IE/ JR G ARI
32( '- --- -- -- -- -- -- -- --- -- --
33( CL
34( IN IT CA I N . ';( )%
34! TX :R( % 0
36( IN IT CH IN/ N ' C
37( IN IT CO IAI '; OMI
37! IM 'X$ = :H' CH '"N "+ MN F" R; ?"
38( CA . I PT (( )% IN TX T :RI R%
39( '
40( ST :AI = I
40! RX :R( % 0
40( CH = AL :H$
40( WH .E KE :OF = I
40( CA . I PT :T CN ;, TR M% R) RR ?%)
41( WE I
41( RX :R( % 0
41( CA . I PN IEF C :NC , RE 4% ME ;(' , AT 3% ), 'WI TY F ER R%
41! PR IT CA I N . '; NO' " IAI AL IO. " CH ; ' AL : ; :AS CH'
42( '
43( IN IT SC I / AI <) ?> AN $
44( IF .N$ =" ' T EN OT 1( 0
44( IN IT SA : ( AN L y,I "; IS$
44( IF .N$ = 'y' TH ( TO 58
44( IF .N$ = 'n' TH ( TO 50
45( ST :%( )=
46( CH :$= I"
47( GO I 1 )
49( RE IRI
10( '- -- -- -- -- -- -- -- --- -- --- -- --
10' ' W TE TO IS
10( '- -- -- -- -- -- -- -- --- -- -- -- --
10( TI IS NE TI )I NE FT DI (
10! MM VA (M $( AT ,1 ?)
10( IF M% 1 EN 4M! "J J"
10( IF M% 2 EN 4M! "F 3"
10( IF M% 3 EN 4M! "M ?"
10( IF M% 4 EN 4M! "A ?"
11( IF M% 5 EN 4M! "M J"
11 IF M% 6 EN 4M! "J J"
12 IF M% 7 EN 4M! "J ."
13 IF M% 8 EN 4M! "A 3"
14 IF M% 9 EN 4M! "S )"
15 IF M% 10 HE MI =" (T'
16 IF M% 11 HE MI =" )V'
17 IF M% 12 HE MI =" EC'
18 )T $= ". ID (D/ E$ ',4 +M I$( AT ,1 2). ID (D/ E$ ,2
19 TT $= ". ID (T E$ I,2 +M I$( IM ,4 2)
20 =I $= A: MN FM $( ATI ,4 !)+ .D. "
24 )PI " ',: ,F .E!
28 ?R T I,I ID :T D$
29 ?R T I,I IN "; ## .# ;S ), (2 ,S 22
30 ?R T I,I IN "; ## #' S( ,S 3) (4 ,S ), 6) S( '), (7 S( I,S 9) (2 )
31 ?R T I,I IN "; ## #' S( I), (1 ,S 12 S( i), (1
32 ?R T I,I IN "; ## #' S( '), (1 ,S 19 S( I), (2 ,S 24 S( i), (2
33 ?R T I,I IN "; ## .#' S( .), (4 ,S 35 S( .), (4 ,S 54
34 ?R T I,I IN "; ## #' S( '), (3 ,S 31 S( !), (3 ,S 34 S( i), (3
35 ?R T I,I IN "; ## #' S( i), (3' ,S 15 S( ), (5
36 ?R T I,I IN "; ## ';S 41 S( 2)
37 ?R T I,I IN "; ## #' S( '), (5 ,S 50 S( i), (5 ,S 58
38 ?R T I,I IN "; ## #' S( '), (6 ,S 51 S( !), (6
39 ?R T I,I IN "; ## #' S( ), (4 ,S 57 S( i)
40 :L( E
41 .O( TE !2, 5 PF NT '
42 .O( TE !2,
43 ?RI T AT : DA E$, ME " IN 6;'
45 .O( TE !2, 5 PF NT '
50 .O( TE !2, 5
60 ?RI T 'II : MI $( LE ,3 ); I ST ;A\ MI $( ME ,1 ); I TE AL " ID :SI 60 ' N N"
63 'OF J% 1 7
64 N (J =' S( ;)=
65 IE) J
70 :ET RN
```

```
3000 '--------------------------------------------
3002 '    CONTROL OF THE DIODS IN THE PLANCHE
3004 '--------------------------------------------
3005 CNO% = 3
3007 TXERROR% = 0
3008 GOTO 3100
3010 CALL IMPTX (CNO%, IMPTX$, TXERROR%)
3024 STREAM% = 0
3025 RXERROR% = 0
3026 WHILE RXERROR% = 0
3027 CALL IMPTEST (CNO%, STREAM%, RXERROR%)
3028 WEND
3029 RXERROR% = 0
3030 CALL IMPNUMERIC (CNO%, STREAM%, RESULT3(1), STATUS%(1), TWENTY%, RXERROR%)
3080 RETURN
3100 '---------SOLAR HEAT TO ROOM 1----------
3110 IF M(14) = 0 THEN GOTO 3135
3120 CON$(1) = "CH7MO801"
3125 CON$(6) = "CH12MO801"
3130 GOTO 3200
3135 CON$(1) = "CH7MO800"
3140 CON$(6) = "CH12MO800"
3200 '---------HEAT EXCHANGER ROOM 1----------
3210 IF M(43) = 0 THEN GOTO 3250
3225 CON$(2) = "CH8MO801"
3227 CON$(6) = "CH12MO800"
3229 CON$(7) = "CH13MO801"
3230 GOTO 3300
3250 CON$(2) = "CH8MO800"
3260 CON$(7) = "CH13MO800"
3300 '---------SOLAR HEAT TO ROOM 2----------
3310 IF M(35) = 0 THEN GOTO 3340
3320 CON$(3) = "CH9MO801"
3325 CON$(8) = "CH14MO801"
3330 GOTO 3400
3340 CON$(3) = "CH9MO800"
3350 CON$(8) = "CH14MO800"
3400 '----------HEAT EXCHANGER ROOM 2----------
3405 IF M(44) = 0 THEN GOTO 3450
3420 CON$(4) = "CH10MO801"
3425 CON$(8) = "CH14MO800"
3427 CON$(9) = "CH15MO801"
3430 GOTO 3500
3450 CON$(4) = "CH10MO800"
3460 CON$(9) = "CH15MO800"
3500 '---------SOLAR HEAT TI ROOM 3----------
3510 IF M(20) = 0 THEN GOTO 3540
3520 CON$(5) = "CH11MO801"
3530 GOTO 3600
3540 CON$(5) = "CH11MO800"
3600 '----------COMMAND----------
3960 IMPTX$ = CON$(1)+";"+CON$(2)+";"+CON$(3)+";"+CON$(4)+";"+CON$(5)+";"+CON$(6)+";"+CON$(7)+";"+CON$(8-
)+";"+CON$(9)+";AR;TR"
3965 GOTO 3010
4000 '--------------------------------------------
4001 ' SCAN MEASURING POINTS
4002 '--------------------------------------------
4021 TIDSCANNEW=TIDSCANNEW+TIDSCAN
4022 CNO% = 1
4023 TXERROR% = 0
4024 IMPTX$ = "TR"
4025 CALL IMPTX (CNO%, IMPTX$, TXERROR%)
4027 STREAM% = 0
4030 RXERROR% = 0
4032 WHILE RXERROR% = 0
4034 CALL IMPTEST (CNO%, STREAM%, RXERROR%)
4038 WEND
4040 RXERROR% = 0
4045 CALL IMPNUMERIC (CNO%, STREAM%, RESULT1(1), STATUS%(1), TWENTY%, RXERROR%)
4047 '
4048 CNO% = 2
4050 TXERROR% = 0
4055 IMPTX$ = "TR"
4060 CALL IMPTX (CNO%, IMPTX$, RXERROR%)
4065 STREAM% = 0
4070 RXERROR% = 0
4072 WHILE RXERROR% = 0
4074 CALL IMPTEST (CNO%, STREAM%, RXERROR%)
```

```
4076 WEND
4078 RXERROR% = 0
4080 CALL IMPNUMERIC (CNO%, STREAM%, RESULT2(1), STATUS%(1), TWENTY%, RXERROR%)
4100 '
4110 CNO% = 3
4120 TXERROR% = 0
4130 IMPTX$ = "TR"
4140 CALL IMPTX (CNO%, IMPTX$, TXERROR%)
4150 STREAM% = 0
4160 RXERROR% = 0
4162 WHILE RXERROR% = 0
4164 CALL IMPTEST (CNO%, STREAM%, RXERROR%)
4166 WEND
4168 RXERROR% = 0
4170 CALL IMPNUMERIC (CNO%, STREAM%, RESULT3(1), STATUS%(1), TWENTY%, RXERROR%)
4180 '
4190 FOR I% = 1 TO 20
4200 M(I%) = RESULT1(I%)
4210 M(20+I%) = RESULT2(I%)
4220 NEXT I%
4230 M(41) = RESULT3(1)
4235 M(42) = RESULT3(2)
4240 RETURN
4400 '-------------------------------------------
4410 '       SWITCH TO OTHER AIR FLOW METERS
4420 '-------------------------------------------
4450 CNO% = 3
4460 TXERROR% = 0
4470 IMPTX$ = "CH3MO801;CH4MO800;CH5MO801;CH6MO800;CH16MO801;AR;TR"
4480 CALL IMPTX (CNO%, IMPTX$, TXERROR%)
4481 STREAM% = 0
4482 RXERROR% = 0
4483 WHILE RXERROR% = 0
4484 CALL IMPTEST (CNO%, STREAM%, RXERROR%)
4485 WEND
4486 RXERROR% = 0
4487 CALL IMPNUMERIC (CNO%, STREAM%, RESULT3(1), STATUS%(1), TWENTY%, RXERROR%)
4490 RETURN
4495 '
4500 GOSUB 1000
4510 WHILE TIDL<TIDSCANNEW-TIDSCAN/2
4520 GOSUB 1000
4525 GOSUB 1260
4530 WEND
4540 RETURN
5000 '------------------------------------------
5010 '       SCAN MEASURING POINTS
5020 '------------------------------------------
5030 CNO% = 1
5040 TXERROR% = 0
5050 IMPTX$ = "TR"
5060 CALL IMPTX (CNO%, IMPTX$, TXERROR%)
5070 STREAM% = 0
5080 RXERROR% = 0
5082 WHILE RXERROR% = 0
5084 CALL IMPTEST (CNO%, STREAM%, RXERROR%)
5086 WEND
5088 RXERROR% = 0
5090 CALL IMPNUMERIC (CNO%, STREAM%, RESULT4(1), STATUS%(1), TWENTY%, RXERROR%)
5100 '
5110 CNO% = 2
5120 TXERROR% = 0
5130 IMPTX$ = "TR"
5140 CALL IMPTX (CNO%, IMPTX$, TXERROR%)
5150 STREAM% = 0
5160 RXERROR% = 0
5162 WHILE RXERROR% = 0
5164 CALL IMPTEST (CNO%, STREAM%, RXERROR%)
5166 WEND
5168 RXERROR% = 0
5170 CALL IMPNUMERIC (CNO%, STREAM%, RESULT5(1), STATUS%(1), TWENTY%, RXERROR%)
5180 '
5190 M(7) = RESULT4(7)
5200 M(8) = RESULT4(8)
5210 M(9) = RESULT4(9)
5220 M(16) = RESULT4(16)
5230 M(43) = RESULT4(14)
5240 M(21) = RESULT5(1)
```

```
5260 M(28) = RESULT5(8)
5270 M(31) = RESULT5(11)
5280 M(32) = RESULT5(12)
5290 M(44) = RESULT5(15)
5300 M(37) = RESULT5(17)
5310 '
5320 CNO% = 3
5330 TXERROR% = 0
5340 IMPTX$ = "CH3M0801;CH4M0800;CH5M0801;CH6M0800;CH16M0801;AR;TR"
5350 CALL IMPTX (CNO%, IMPTX$, TXERROR%)
5351 STREAM% = 0
5352 RXERROR% = 0
5354 WHILE RXERROR% = 0
5355 CALL IMPTEST (CNO%, STREAM%, RXERROR%)
5356 WEND
5357 RXERROR% = 0
5358 CALL IMPNUMERIC (CNO%, STREAM%, RESULT3(1), STATUS%(1), TWENTY%, RXERROR%)
5360 RETURN
5400 '-------------------------------------------
5405 '    EFFECICIENCIES
5410 '-------------------------------------------
5415 IF M(43) = 0 GOTO 5435
5420 M(56) = M(49)/M(52)*100
5425 EFF1 = M(56)
5427 IND1 = M(49)
5430 GOTO 5470
5435 IF M(14) = 0 GOTO 5460
5440 M(64) = M(49)/(M(1)*56.16)*100
5445 EFF1 = M(64)
5447 IND1 = M(62)
5450 M(56) = 0
5455 GOTO 5470
5460 M(64) = 0
5465 EFF1 = 0
5467 IND1 = 0
5470 '
5475 IF M(44) = 0 GOTO 5495
5480 M(57) = M(50)/M(53)*100
5485 EFF2 = M(57)
5487 IND2 = M(50)
5490 GOTO 5530
5495 IF M(35) = 0 GOTO 5520
5500 M(65) = M(50)/(M(1)*56.16)*100
5505 EFF2 = M(65)
5507 IND2 = M(63)
5510 M(57) = 0
5515 GOTO 5530
5520 M(65) = 0
5525 EFF2 = 0
5527 IND2 = 0
5530 '
5535 IF M(40) = 0 GOTO 5555
5540 M(66) = M(51)/(M(1)*14.04)*100
5545 EFF3 = M(66)
5547 IND3 = M(61)
5550 GOTO 5565
5555 M(66) = 0
5560 EFF3 = 0
5562 IND3 = 0
5565 '
5570 RETURN
6000 '-------------------------------------------
6010 '    PRINT TO SCREAN
6020 '-------------------------------------------
6040 LOCATE 1,1
6050 PRINT "                ---------------WEATHER DATA----------------------"
6070 LOCATE 2,15 : PRINT "IRR: "
6075 LOCATE 2,20 : PRINT USING "#####";M(1)
6078 LOCATE 2,25 : PRINT " W  AMB TEMP: "
6079 LOCATE 2,39 : PRINT USING "##.#";M(21)
6080 LOCATE 2,44 : PRINT " C  RH: "
6081 LOCATE 2,52 : PRINT USING "###.#";M(22)
6082 LOCATE 2,57 : PRINT " %";"     "
6083 LOCATE 3,1
6084 PRINT "                ----------------SYSTEM DATA----------------------"
6085 LOCATE 4,1
6086 PRINT "                                  ROOM 1  ROOM 2  ROOM 3       "
6087 LOCATE 5,15 : PRINT "                                                  "
```

```
6088 LOCATE 5,15 : PRINT "ROOM TEMP   [C]    "
6089 LOCATE 5,32 : PRINT USING "######.#";M(2);M(29);M(38)
6090 LOCATE 6,15 : PRINT "                                                        "
6092 LOCATE 6,15 : PRINT "RH          [%]    "
6093 LOCATE 6,32 : PRINT USING "######.#";M(3);M(30)
6095 LOCATE 7,15 : PRINT "                                                        "
6097 LOCATE 7,15 : PRINT "FLOW IN     [m3/h]"
6098 LOCATE 7,32 : PRINT USING "########";M(14);M(35);M(40)
6101 LOCATE 8,15 : PRINT "                                                        "
6103 LOCATE 8,15 : PRINT "FLOW OUT    [m3/h]"
6104 LOCATE 8,32 : PRINT USING "########";M(43);M(44)
6107 LOCATE 9,15 : PRINT "                                                        "
6109 LOCATE 9,15 : PRINT "TEMP IN     [C]    "
6110 LOCATE 9,32 : PRINT USING "######.#";M(45);M(46);M(39)
6113 LOCATE 10,15 : PRINT "                                                       "
6115 LOCATE 10,15 : PRINT "TEMP OUT    [C]    "
6116 LOCATE 10,32 : PRINT USING "######.#";M(47);M(48)
6119 LOCATE 11,15 : PRINT "                                                       "
6121 LOCATE 11,15 : PRINT "ENERGY IN   [W]    "
6122 LOCATE 11,32 : PRINT USING "########";IND1;IND2;IND3
6125 LOCATE 12,15 : PRINT "                                                       "
6127 LOCATE 12,15 : PRINT "ENERGY OUT [W]    "
6128 LOCATE 12,32 : PRINT USING "########";M(52);M(53)
6131 LOCATE 13,15 : PRINT "                                                       "
6133 LOCATE 13,15 : PRINT "EFF EX/COL [%]    "
6134 LOCATE 13,32 : PRINT USING "######.#";EFF1;EFF2;EFF3
6137 LOCATE 14,1
6139 PRINT "                    ---------------OTHER PARAMETERS------------------"
6140 LOCATE 15,15 : PRINT "                                                       "
6141 LOCATE 15,15 : PRINT "GAS TO BOILER  "
6143 LOCATE 15,30 : PRINT USING "###.#";M(54)
6145 LOCATE 15,36 : PRINT "m3/h ="
6147 LOCATE 15,45 : PRINT USING "#####";M(58)
6149 LOCATE 15,51 : PRINT "W               "
6150 LOCATE 16,15 : PRINT "BYPASS: ";BYPASS$;"                                        "
6151 LOCATE 17,1
6153 PRINT "                    ---------TEMPERATURES IN THE MF-PANEL-----------"
6154 LOCATE 18,15 : PRINT "                                                       "
6155 LOCATE 18,15 : PRINT "TEMP IN    [C] "
6157 LOCATE 18,28 : PRINT USING "#######.#";M(23);M(24);M(25);M(26)
6158 LOCATE 19,15 : PRINT "                                                       "
6159 LOCATE 19,15 : PRINT "TEMP OUT   [C] "
6161 LOCATE 19,28 : PRINT USING "#######.#";M(17);M(18);M(19);M(20)
6199 RETURN
6300 '-------------------------------------------
6310 '     CONSUMPTION OF GAS
6320 '-------------------------------------------
6330 DIFF = M(41)-DIFFOLD1
6340 IF DIFF > 0 THEN GOTO 6352
6345 IF DIFF=0 THEN GOTO 6352
6350 DIFF = M(41)+16777216#-DIFFOLD1
6352 DIFFOLD1 = M(41)
6355 M(41) = DIFF*.02/60
6360 M(54) = M(41)*6.21
6365 M(58) = M(54)*10858
6400 '-------------------------------------------
6410 '     BYPASS
6420 '-------------------------------------------
6430 DIFF = M(42)-DIFFOLD2
6440 IF DIFF > 0 THEN GOTO 6490
6442 IF DIFF = 0 THEN GOTO 6460
6445 DIFF = M(42)+16777216#-DIFFOLD1
6447 IF DIFF > 0 GOTO 6490
6460 BYPASS$ = "CLOSED"
6470 GOTO 6510
6490 BYPASS$ = "OPEN  "
6510 DIFFOLD2 = M(42)
6515 M(42) = DIFF*.02/60
6520 RETURN
7300 '------------------------------------------
7305 '       AIR FLOWS
7310 '------------------------------------------
7312 IF M(14) < .2 THEN GOTO 7318
7313 RO(1) = EXP(.2576-.00323*M(6))
7314 M(14) = 64.32*SQR((.913*M(14)-.11)*9.807)+1.8
7315 M(14) = M(14)*SQR(1.2/RO(1))*4.22
7316 IF M(14) > 100 THEN GOTO 7320
7318 M(14) = 0
```

```
7320 '
7321 IF M(35) < .1 THEN GOTO 7330
7322 RO(2) = EXP(.2576-.00323*M(36))
7324 M(35) = 282*SQR((1.24*M(35)-.1)*9.807)+11.31
7326 M(35) = M(35)*SQR(1.2/RO(2))
7328 IF M(35) > 200 THEN GOTO 7332
7330 M(35) = 0
7332 '
7333 IF M(40) < .1 THEN GOTO 7338
7334 RO(3)=EXP(.2576-.00323*M(15))
7335 M(40) = 64.32*SQR((1.36*M(40)-.11)*9.807)+1.8
7336 M(40)=M(40)*SQR(1.2/RO(3))
7337 IF M(40) > 100 THEN GOTO 7350
7338 M(40) = 0
7350 '
7351 IF M(43) < .2 THEN GOTO 7358
7352 RO(4) = EXP(.2576-.00323*M(16))
7353 M(43) = 64.32*SQR((.913*M(43)-.11)*9.807)+1.8
7354 M(43) = M(43)*SQR(1.2/RO(4))*3.57
7356 IF M(43) > 100 THEN GOTO 7360
7358 M(43) = 0
7360 '
7361 IF M(44) < .1 THEN GOTO 7370
7362 RO(5) = EXP(.2576-.00323*M(37))
7364 M(44) = 282*SQR((1.24*M(44)-.1)*9.807)+11.31
7366 M(44) = M(44)*SQR(1.2/RO(5))
7368 IF M(44) > 200 THEN GOTO 7372
7370 M(44) = 0
7372 RETURN
7400 '------------------------------------------
7405 '       ENERGY FLOWS
7410 '------------------------------------------
7416 M(45) = (M(4)*1.16+M(5)*.98+M(6)*.95+M(27)*.91)/4
7417 M(49) = 1005*RO(1)*M(14)*(M(45)-M(21))/3600
7418 IF M(43) = 0 THEN GOTO 7422
7419 M(59) = 0
7420 M(62) = 0
7421 GOTO 7424
7422 M(59) = M(49)
7423 M(62) = 1005*RO(1)*M(14)*(M(45)-M(2))/3600
7424 '
7426 M(46) = (M(33)+M(34))/2
7427 M(50) = 1005*RO(2)*M(35)*(M(46)-M(21))/3600
7428 IF M(44) = 0 THEN GOTO 7432
7429 M(60) = 0
7430 M(63) = 0
7431 GOTO 7434
7432 M(60) = M(50)
7433 M(63) = 1005*RO(2)*M(35)*(M(46)-M(29))/3600
7434 '
7438 M(51) = 1005*RO(3)*M(40)*(M(39)-M(21))/3600
7439 M(61) = 1005*RO(3)*M(40)*(M(39)-M(38))/3600
7444 '
7454 M(47) = (M(7)*1.08+M(8)*.95+M(9)*1.12+M(28)*.85)/4
7456 M(52) = 1005*RO(4)*M(43)*(M(47)-M(21))/3600
7462 '
7466 M(48) = (M(31)+M(32))/2
7468 M(53) = 1005*RO(5)*M(44)*(M(48)-M(21))/3600
7502 '
7504 RETURN
7510 '------------------------------------------
7511 '       MEAN VALUES
7512 '------------------------------------------
7515    FOR J%=1 TO 3
7517    S(J%)=(S(J%)*(N%(J%)-1)+M(J%))/N%(J%)
7519    N%(J%)=N%(J%)+1
7521    NEXT J%
7523    FOR J%=4 TO 6
7525    IF M(14)=0 THEN GOTO 7531
7527    S(J%)=(S(J%)*(N%(J%)-1)+M(J%))/N%(J%)
7529    N%(J%)=N%(J%)+1
7531    S(J%)=S(J%)
7532    NEXT J%
7533    FOR J%=7 TO 10
7535    IF M(43)=0 THEN GOTO 7541
7537    S(J%)=(S(J%)*(N%(J%)-1)+M(J%))/N%(J%)
7539    N%(J%)=N%(J%)+1
7541    S(J%)=S(J%)
```

```
7542    NEXT J%
7543    FOR J%=11 TO 14
7545    IF M(14)=0 THEN GOTO 7550
7547    S(J%)=(S(J%)*(N%(J%)-1)+M(J%))/N%(J%)
7549    N%(J%)=N%(J%)+1
7550    S(J%)=S(J%)
7551    NEXT J%
7552    J%=16
7553    IF M(43)=0 THEN GOTO 7556
7554    S(J%)=(S(J%)*(N%(J%)-1)+M(J%))/N%(J%)
7555    N%(J%)=N%(J%)+1
7556    S(J%)=S(J%)
7558    FOR J%=17 TO 26
7559    S(J%)=(S(J%)*(N%(J%)-1)+M(J%))/N%(J%)
7560    N%(J%)=N%(J%)+1
7561    NEXT J%
7562    J%=27
7563    IF M(14)=0 THEN GOTO 7566
7564    S(J%)=(S(J%)*(N%(J%)-1)+M(J%))/N%(J%)
7565    N%(J%)=N%(J%)+1
7566    S(J%)=S(J%)
7567    J%=28
7568    IF M(43)=0 THEN GOTO 7571
7569    S(J%)=(S(J%)*(N%(J%)-1)+M(J%))/N%(J%)
7570    N%(J%)=N%(J%)+1
7571    S(J%)=S(J%)
7572    FOR J%=29 TO 30
7573    S(J%)=(S(J%)*(N%(J%)-1)+M(J%))/N%(J%)
7574    N%(J%)=N%(J%)+1
7575    NEXT J%
7576    FOR J%=31 TO 32
7577    IF M(44)=0 THEN GOTO 7580
7578    S(J%)=(S(J%)*(N%(J%)-1)+M(J%))/N%(J%)
7579    N%(J%)=N%(J%)+1
7580    S(J%)=S(J%)
7581    NEXT J%
7584    FOR J%=33 TO 36
7585    IF M(35)=0 THEN GOTO 7588
7586    S(J%)=(S(J%)*(N%(J%)-1)+M(J%))/N%(J%)
7587    N%(J%)=N%(J%)+1
7588    S(J%)=S(J%)
7589    NEXT J%
7590    J%=37
7591    IF M(44)=0 THEN GOTO 7594
7592    S(J%)=(S(J%)*(N%(J%)-1)+M(J%))/N%(J%)
7593    N%(J%)=N%(J%)+1
7594    S(J%)=S(J%)
7595    J%=38
7596    S(J%)=(S(J%)*(N%(J%)-1)+M(J%))/N%(J%)
7597    N%(J%)=N%(J%)+1
7598    FOR J%=39 TO 40
7599    IF M(40)=0 THEN GOTO 7602
7600    S(J%)=(S(J%)*(N%(J%)-1)+M(J%))/N%(J%)
7601    N%(J%)=N%(J%)+1
7602    S(J%)=S(J%)
7603    NEXT J%
7604    FOR J%=41 TO 42
7605    S(J%)=S(J%)+M(J%)
7607    NEXT J%
7608    J%=43
7609    IF M(43) = 0 THEN GOTO 7612
7610    S(J%)=(S(J%)*(N%(J%)-1)+M(J%))/N%(J%)
7611    N%(J%)=N%(J%)+1
7612    S(J%)=S(J%)
7616    J%=44
7617    IF M(44) = 0 THEN GOTO 7621
7618    S(J%)=(S(J%)*(N%(J%)-1)+M(J%))/N%(J%)
7620    N%(J%)=N%(J%)+1
7621    S(J%)=S(J%)
7636    FOR J%=49 TO 54
7640    S(J%)=(S(J%)*(N%(J%)-1)+M(J%))/N%(J%)
7642    N%(J%)=N%(J%)+1
7644    NEXT J%
7648    J%=45
7650    IF M(14)=0 THEN GOTO 7656
7652    S(J%)=(S(J%)*(N%(J%)-1)+M(J%))/N%(J%)
7654    N%(J%)=N%(J%)+1
7656    S(J%)=S(J%)
```

```
7660    J%=46
7661    IF M(35) = 0 THEN GOTO 7665
7662    S(J%)=(S(J%)*(N%(J%)-1)+M(J%))/N%(J%)
7664    N%(J%)=N%(J%)+1
7665    S(J%)=S(J%)
7668    J%=47
7670    IF M(43)=0 THEN GOTO 7676
7672    S(J%)=(S(J%)*(N%(J%)-1)+M(J%))/N%(J%)
7674    N%(J%)=N%(J%)+1
7676    S(J%)=S(J%)
7680    J%=48
7682    IF M(44) = 0 THEN GOTO 7688
7684    S(J%)=(S(J%)*(N%(J%)-1)+M(J%))/N%(J%)
7686    N%(J%)=N%(J%)+1
7688    S(J%)=S(J%)
7689    J%=15
7691    IF M(40)=0 THEN GOTO 7694
7692    S(J%)=(S(J%)*(N%(J%)-1)+M(J%))/N%(J%)
7693    N%(J%)=N%(J%)+1
7694    S(J%)=S(J%)
7696    J%=56
7697    IF M(43)=0 THEN GOTO 7700
7698    S(J%)=(S(J%)*(N%(J%)-1)+M(J%))/N%(J%)
7699    N%(J%)=N%(J%)+1
7700    S(J%)=S(J%)
7701    J%=57
7702    IF M(44)=0 THEN GOTO 7705
7703    S(J%)=(S(J%)*(N%(J%)-1)+M(J%))/N%(J%)
7704    N%(J%)=N%(J%)+1
7705    S(J%)=S(J%)
7706    FOR J%=58 TO 63
7707    S(J%)=(S(J%)*(N%(J%)-1)+M(J%))/N%(J%)
7708    N%(J%)=N%(J%)+1
7709    NEXT J%
7710 RETURN
7720 '------------------------------------------
7722 '        SOLAR IRRADIATION + HUMIDITY
7725 '------------------------------------------
7730 M(1) = M(1)/4.75E-06
7740 '
7750 M(3) = M(3)*10*1.2
7760 M(22) = M(22)*10
7770 M(30) = M(30)*10*1.1
7780 RETURN
8000 '------------------------------------------
8010 '      INITIALIZATION
8020 '------------------------------------------
8030 CLS
8050 TIDDISK=1800 :TIDSCAN=60
8060 TWENTY%  = 20
8070 DIFFOLD1 = 0
8080 DIFFOLD2 = 0
8090 '
8100 KEY OFF
8110 FOR I% = 1 TO 2
8120     READ CARDADDRESS%( I% )
8130 NEXT
8140 DATA &HA000 , &HD000
8150 '
8160     ADDR% = 2
8170 CARDADDRESS% = CARDADDRESS% ( ADDR% )
8180 '
8190 BLOAD "IMPDRIVE.MAC",DRIVERADDRESS%
8200 '
8210 IMPTX       = DRIVERADDRESS%
8220 IMPTEST     = DRIVERADDRESS% + 3
8230 IMPNUMERIC  = DRIVERADDRESS% + 6
8240 IMPSTRING   = DRIVERADDRESS% + 9
8250 IMPINIT     = DRIVERADDRESS% + 12
8260 '
8270 FOR I% = 1 TO 30
8280     ATTACHED% (I%) = 0
8290 NEXT
8300     NUMBER.OF.IMPS% = 3
8310 CLS
8320 LOCATE 12,1
8330 FOR I% = 1 TO NUMBER.OF.IMPS%
8340     ATTACHED% ( I% ) = 1
```

```
8350     IMPADDRESS% ( I% ) = I%
8360 NEXT
8370 '
8380 FOUND% = 0
8480 CALL IMPINIT ( CARDADDRESS% , ATTACHED% ( 1 ) , FOUND% )
8500 '
8510 ' Transmit setup to IMPS
8520 '
8530 IMPTX$ = "RE;SE"
8540 TXERROR% = 0
8550 FOR I% = 1 TO NUMBER.OF.IMPS%
8560     CALL IMPTX ( IMPADDRESS% ( I% ) , IMPTX$ , TXERROR% )
8580 NEXT
8600 '
8610 CNO% = 1
8612 TXERROR% = 0
8614 IMPTX$ = "CH1MO100;CH2MO360;CH3MO104;CH4MO360;CH5MO360;CH6MO360;CH7MO360;CH8MO360;CH9MO360;C-
H10MO360;CH11MO360;CH12MO360;CH13MO360;CH14MO104;CHA15MO360;CH16MO360;CH17MO360;CH18MO360;CH19MO-
360;CH20MO360;AR"
8616 CALL IMPTX (CNO%, IMPTX$, TXERROR%)
8620 CNO% = 2
8622 TXERROR% = 0
8624 IMPTX$ = "CH1MO360;CH2MO104;CH3MO360;CH4MO360;CH5MO360;CH6MO360;CH7MO360;CH8MO360;CH9MO360;C-
H10MO104;CH11MO360;CH12MO360;CH13MO360;CH14MO360;CH15MO104;CH16MO360;CH17MO360;CH18MO360;CH19MO3-
60;CH20MO104;AR"
8626 CALL IMPTX (CNO%, IMPTX$, TXERROR%)
8634 CNO% = 3
8636 TXERROR% = 0
8638 IMPTX$ = "CH1MO740;CH2MO740;CH3MO800;CH4MO801;CH5MO800;CH6MO801;CH16MO801;AR;TR"
8640 CALL IMPTX (CNO%, IMPTX$, TXERROR%)
8642 STREAM% = 0
8643 RXERROR% = 0
8644 WHILE RXERROR% = 0
8645 CALL IMPTEST (CNO%, STREAM%, RXERROR%)
8646 WEND
8647 RXERROR% = 0
8648 CALL IMPNUMERIC (CNO%, STREAM%, RESULT3(1), STATUS%(1), TWENTY%, RXERROR%)
8650 '
8660 FOR J% = 1 TO 70
8670     N%(J%) = 1
8680 NEXT J%
8700 GOSUB 1000
8702 A1=INT(SEK/TIDSCAN)
8707 A2=INT(SEK/TIDDISK)
8712 TIDSCANNEW=A1*TIDSCAN+TIDSCAN
8715 TIDDISKNEW=TIDDISK*(A2+1)
8800 GOSUB 4000
8810 GOSUB 5000
8990 RETURN
9000 '------------------------------------------
9010 '   MANUEL OPERATION
9020 '------------------------------------------
9025 STYR%(1)=1
9030 CLS
9035 PRINT "CONTROL OF THE POSTER SHOWING THE OPERATION MODE OF THE SYSTEM"
9040 PRINT "TYPE 0 OR 1 FOR THE 5 FLOW RATES IN THE SYSTEM"
9060 INPUT "FLOW TO ROOM 1:  ";M(14)
9070 INPUT "FLOW FROM ROOM 1:  ";M(43)
9080 INPUT "FLOW TO ROOM 2:  ";M(35)
9090 INPUT "FLOW FROM ROOM 2:  ";M(44)
9100 INPUT "FLOW TO ROOM 3:  ";M(40)
9110 GOSUB 3000
9112 '
9115 INPUT "DO YOU WANT TO OPERATE THE MAGNETIC VALVES <y/n>: ";ANS$
9120 IF ANS$="n" GOTO 9195
9125 INPUT "TYPE 0 FOR SETTING >FLOW IN< AND 1 FOR >FLOW OUT<";ANS2%
9127 IF ANS2%=1 GOTO 9137
9129 INP1$="CH3MO800"
9131 INP2$="CH4MO801"
9133 INP3$="CH5MO800"
9135 INP4$="CH6MO801"
9136 GOTO 9145
9137 INP1$="CH3MO801"
9139 INP2$="CH4MO800"
9141 INP3$="CH5MO801"
9143 INP4$="CH6MO800"
9145 CNO%=3
9147 TXERROR%=0
```

```
9149 IMPTX$=INP1$+";"+INP2$+";"+INP3$+";"+INP4$+"AR;TR;"
9151 CALL IMPTX (CNO%, IMPTX$, TXERROR%)
9153 '
9185 INPUT "NEW TRY <y/n>: ";ANS$
9190 IF ANS$="y" THEN GOTO 9000
9195 GOTO 500
9200 IF STYR%(2)=0 THEN STY%=1
9210 IF STYR%(2)=1 THEN STY%=0
9220 STYR%(2)=STY%
9230 GOTO 500
9300 STYR%(1)=2
9310 GOTO 500
9999 END
```

Appendix D

Integrated Energy Producing Building Component

The concept introduced in this proposal comprises several already known thermo physical processes combined in a new and fully integraded way: Photovoltaric generation of electricity, solar heated air, heat exchange between fresh air and exhaust air from a building and solar heated domestic hot water.

Background

"The Integrated Energy Producing Building component" (IEPB-component) is based on the "Multi-Function solar energy facade or roof panel" (MF-panel). The MF-panel is constructed to adapt a facade often used for industrial buildings, a facade with corrugated metal profiles. Besides being the wall (or the roof) of a house the MF-panel 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 - see figure 1. The panels have, furthermore, a smaller heat loss to the surroundings than a normal wall (or roof). Instead of using the warm air from the MF-panel as pre-heated fresh air, it can be used for pre-heating of domestic hot water or for other processes which need heat at low temperatures.

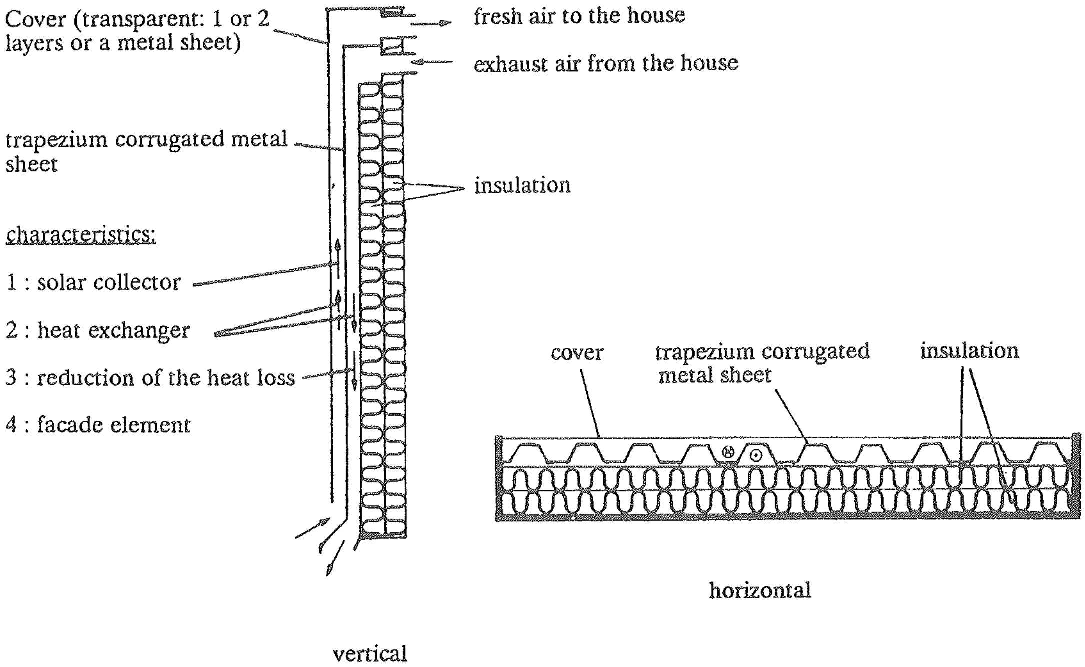

Figure 1. Outline of a Multi-Function solar energy panel serving as pre-heater of fresh air.

Tests have been carried out on MF-panels showing a collector efficiency of up to 65% (figure 2) and a heat exchanger efficiency of about 30% depending on the air flow through the panel (figure 3) (ref. [1] and [2]). Simulations have further shown an annual performance of between 250 and 1350 kWh/m^2 (depending on the flow per m^2) under Danish weather conditions.

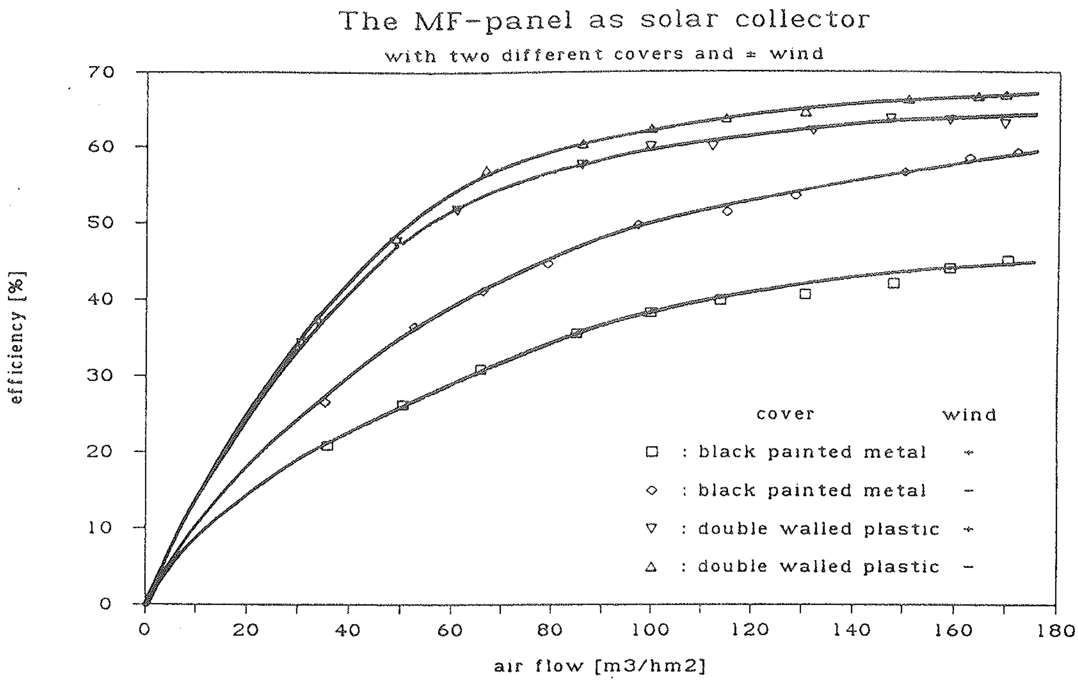

Figure 2. Results from tests made on a MF-panel used for preheating of air. The efficiency has been measured with a transparent cover and with at black painted steel plate as cover. The efficiency has further been measured with and without a simulated influence of a wind speed of 2 m/s along the cover.

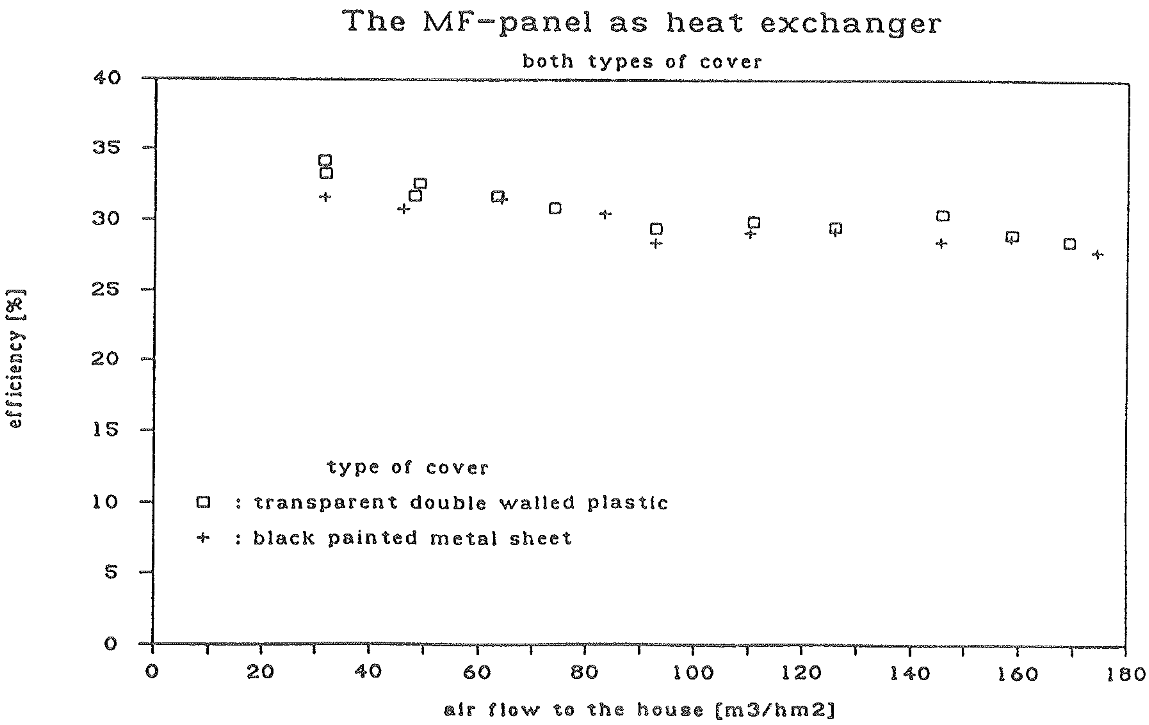

Figure 3. Results from tests made on a MF-panel used as a heat exchanger between fresh air and exhaust air from a building. The efficiency has been measured with and without a transparent cover and a black painted steel plate as cover

Outline of the Integrated Energy Producing Building component

By mounting panels of solar cells in the cover of the MF-panel (see figure 4 and 5) it is possible to create an "autonomous" or "stand alone" unit producing the electricity needed for system operation - ventilators, dampers, etc of the component - but also electricity for safety and security sub-systems.

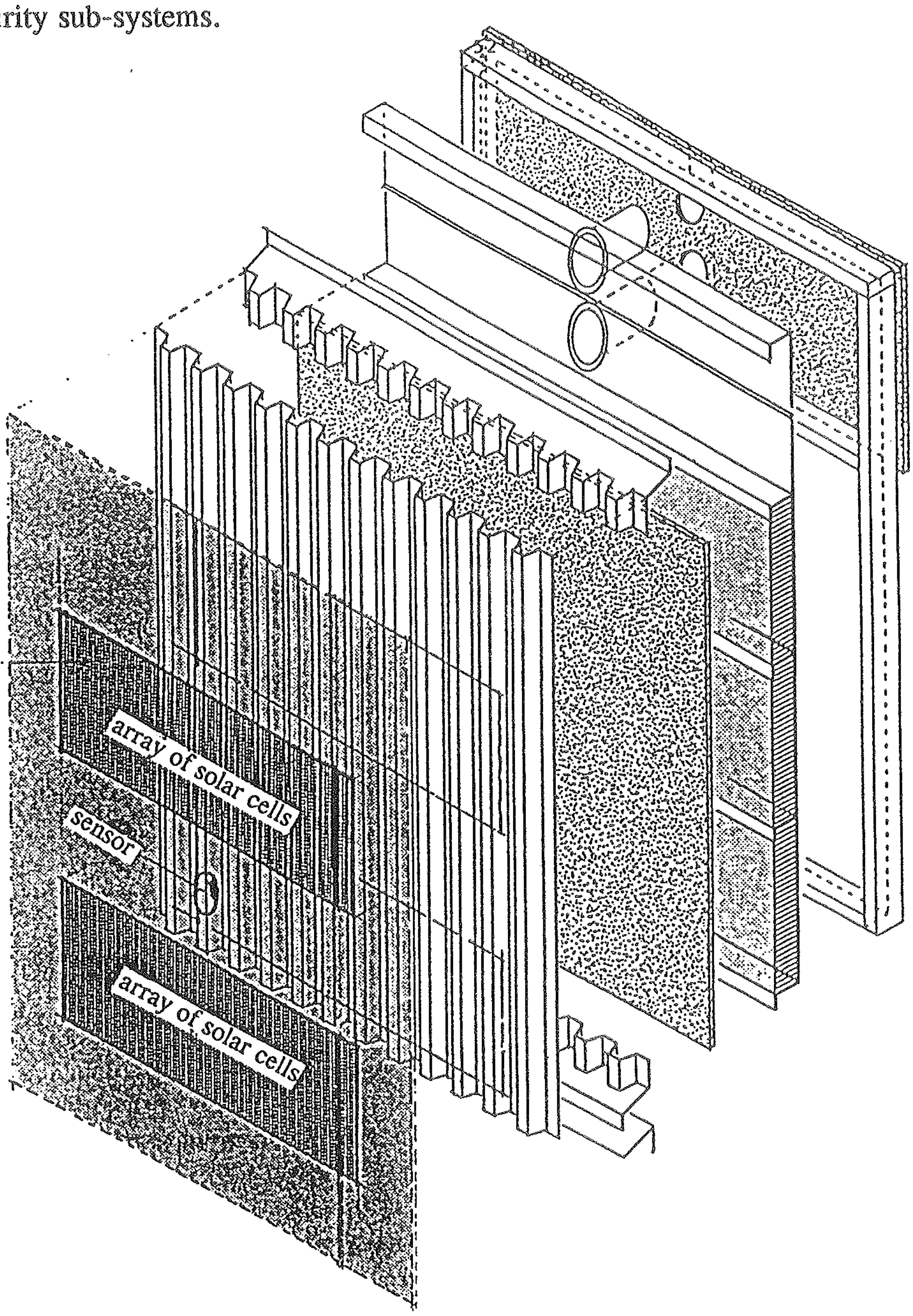

Figure 4. MF-panel with solar cells installed in the cover. The solar cells should be mounted in the lower part of the cover, and not as shown here quite high up in the cover.

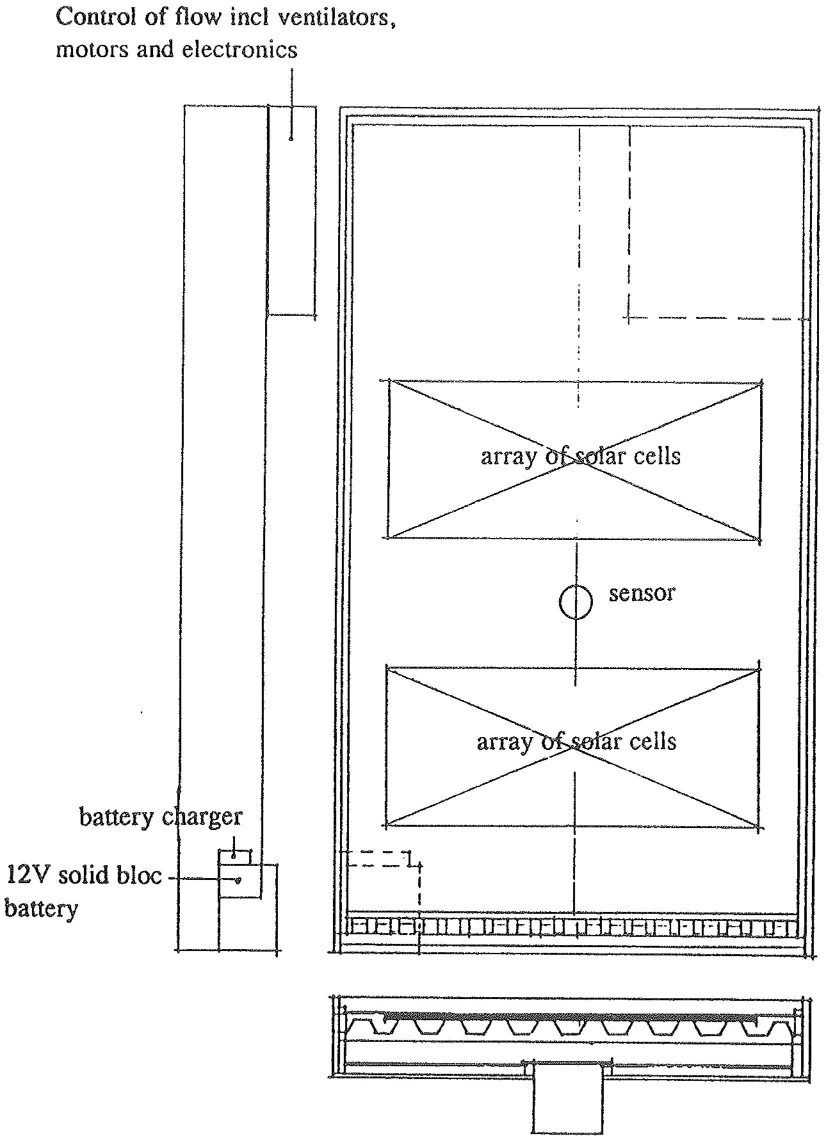

Figure 5. Outline of a combined solar cell/solar collector panel with heat exchanger and autonomous energy supply for regulation and other purposes: Integrated Energy Producing Building component. The solar cells will be placed in the lower part of the cover.

The reason for mounting the solar cells in the cover is, that the efficiency of solar cells decrease with increasing temperature of the solar cells. By mounting the cells in the cover the solar cells can be cooled by the incoming air, if the solar cells are in good thermal contact with the air - see figure 6. In order to decrease the temperature of the solar cells as much as possible the solar cells should be mounted in the lower part of the cover, as the air here is coldest. The practical efficiency of solar cells is today approximately 15%. It is estimated that this efficiency can be raised by at least 10% by cooling the solar cells. The waste heat from the cooling process contributes to the preheating of the air flowing behind the cover. It is estimated that about 40% of the solar irradiation hitting the solar cells can be utilized in this way.

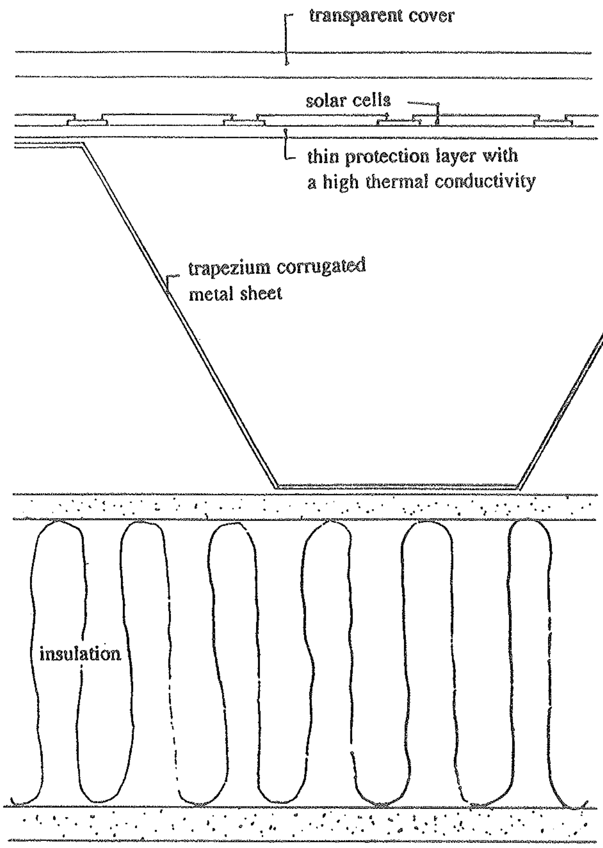

Figure 6. Section of the IEPB-component showing how the solar cells will be cooled by the air flow in the component.

If about 20% of the cover of the IEPB-component is covered with solar cells, the panel should be able to produce enough electricity to cover its own needs and furthermore give a surplus to other electricity consuming equipment of the building. In the morning and evening with low solar radiation the electricity produced by the solar cells is not sufficient to run the ventilator(s) at full speed. But during this time it is often desirable to have a smaller air flow in the component in order to increase the temperature of the air leaving the component, so it is an advantage to run the ventilator(s) at a lower speed during these periods. The electricity generated by the solar cells can furthermore receive a supplement from batteries where electricity from periods with too much generated electricity is stored.

There is no need for preheating of ventilation air in Greece during large periods of the year. The preheated air is therefore used for preheating of domestic hot water. Figure 7 shows two different ways of preheating domestic hot water by means of an IEPB-component: Either by tubes integrated in the component or in an air to water heat exchanger located after the component. The first solution is more expensive than the latter, but consumes less electricity as no ventilator is necessary in order to transport the heat. But as electricity is generated by the element itself, an air to water heat exchanger is probably the best solution. It is foreseen to use a low cost air to water heat exchanger of plastic - figure 8. This kind of ventilators have been shown to have an efficiency of approximately 50% (ref. 3)

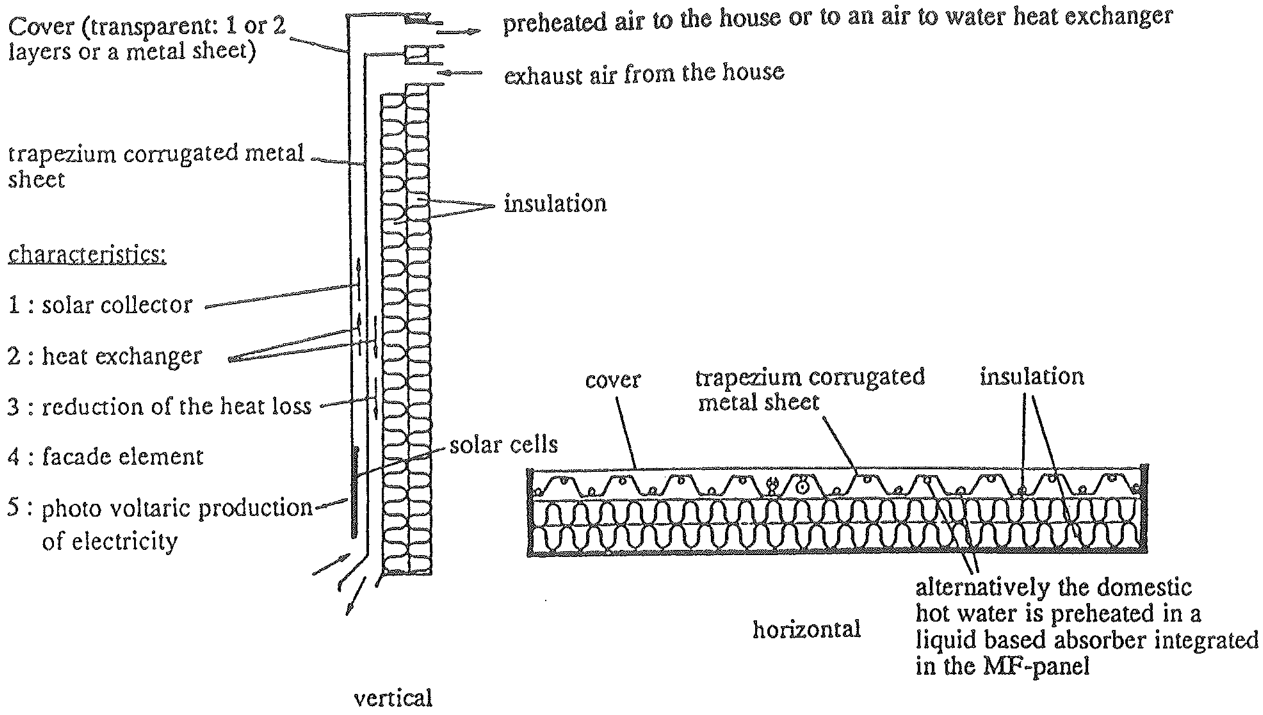

Figure 6. Outline IEPB-component used as a solar collector and a heat exchanger for preheating of fresh air and domestic hot water. Domestic hot water is prepared in an air to water heat exchanger following the IEPB-component or in tubes integrated in the IEPB-component.

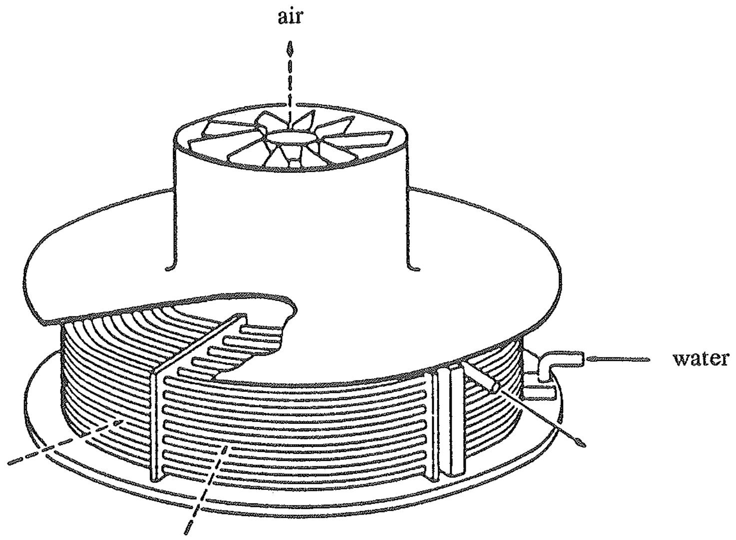

Figure 7. Outline of a low cost air to water heat exchanger of plastic.

The IEPB-component can be produced by means of commercially available components. It is believed that major savings can be obtained in mounting and maintenance compared to other solar systems, as the energy producing and energy saving systems are incorporated in the thermal envelope. Materials of a standard wall or roof can, therefore, be saved.

It is believed that the IEPB-component should mainly be utilized in larger commercial buildings with large demands for space heating and/or domestic hot water production, ventilation and autonomously produced electricity - in a hotel this electricity could be used as back-up for the safety and security systems. The benefit of the IEPB-component will increase when used in remote areas or in areas with an unstable energy supply.

Test and demonstration unit

It is the intention to construct two or more units of the IEPB-component for test and demonstration purposes in the beginning of the project - there will be small design and arcitecturally differences between the units. The test and demonstration units will be constructed by the Danish proposers and tested in the artificial sun at the Thermal Insulation Laboratory.

The test of a test unit of the IEPB-component is necessary in order to gain important informations about the increase of the efficiency of the solar cells due to cooling, how large a part of the waste heat from this cooling that can be recovered, control of the electricity production and consumption, how best to incorporate the component in the building structure, etc. The results from the test of the test units together with the results from former investigations of the MF-panel concept (ref. 1) will be used when designing the demonstration project.

The prototype will be constructed as a "stand alone" unit with ventilators, batteries, control system, etc in order to be used as a demonstration unit.

Demonstration project

The demonstration project itself will consist of 100 m^2 of IEPB-components installed on the Hilton hotel in Athens, Greece. Approximately 20 m^2 of the 100 m^2 will be covered with solar cells.

The hotel is a 9 storey building with 450 rooms.

The IEPB-component will be connected to the existing ventilation system of the hotel and through an air to water heat exchanger to the domestic hot water system of the hotel.

The solar cells will produce electricity for the running of the IEPB-components and to the emergency system of the hotel - emergency lights, fire alarms, etc - through at accumulator, but also to other electricity consuming equipments of the hotel when a surplus of electricity is produced. The solar cells will produce electricity whenever there is solar irradiation enough.

There is only need for preheating of the ventilation air during winter-time - the heating season is from November the 1st to April the 15th . During this period the IEPB-component will preheat fresh air by solar heat during day-time when the solar irradiation is high, and preheat fresh air by heat exchange between fresh air and exhaust air during the nights and during periods with low solar irradiation.

During the rest of the year with no need for preheating of the fresh air, the incoming air from the IEPB-component will be directed to an air to water heat exchanger, when the temperature of the air from the IEPB-component is sufficiently high to contribute to preheating of domestic hot water.

Facilities for preventing the temperature of the IEPB-components from exceeding 80-90 °C will be integrated in the system.

A control strategy for controlling the above-mentioned functions of the IEPB-components will be developed.

It is the aim to integrate the IEPB-components in the building structure of the hotel in an architecturally good way.

It is anticipated that the IEPB-component will have the following performance:

> The efficiency of the solar cells will be increased by approximately 10% to 16.5%. The annual solar irradiation of the region, where the hotel is located, is about 1700 kWh/m^2 on a tilted plane. It is anticipated that the IEPB-components themselves will consume about 50 % of the generated electricity. This leaves 2,800 kWh per year for other purposes of the hotel.
>
> The efficiency of the preheating of fresh air by solar heat will be around 55%, as the cover of the IEPB-component will be transparent. The irradiation during the heating season for the region is about 600 kWh/m^2. Not all of this solar irradiation can be used as sometime only temperatures lower than the air temperature of the building can be produced. It will however help to increase the efficiency of the heat exchanger. It should also be remembered, that only about 40% of the solar irradiation hitting the solar cells can be utilized for preheating purposes. The energy gain during the heating period is foreseen to be 29,000 kWh.
>
> The efficiency of the heat exchanger will be about 30%. An energy saving of 14,800 kWh can, therefore, be foreseen from this operational mode during the heating season, as the mean ambient temperature is 11.9 °C during this period.
>
> The efficiency of the preheating of domestic hot water will be somewhat lower that if traditional flat plate collectors were used. A system efficiency of about 25% can be foreseen, and again only 40% of the solar irradiation hitting the solar cells will be utilized for preheating purposes. This gives an annual performance of 24.500 kWh
>
> The total generated energy from the system to the building is thus anticipated to be 2,800 kWh electricity and 68,300 kWh heat. The saved amount of heat should have been produced by a boiler. The efficiency of this boiler is estimated to be 75%, this means that 91,000 kWh heat actually is saved

With a gasoil price of approximately 0.25 DKK/kWh and an electricity price of about 0.82 DKK/kWh this gives an annual saving of 25,000 DKK.

The system is anticipated to cost 450.000 DKK. If the system was installed in connection with the construction of a building and it was commercially available the cost of the system is estimated to be 200-300.000 DKK depending on the type of wall or roof the IEPB-component replaces, as the cost of the replaced wall or roof can be subtracted the price of the IEPB-component. This gives a simple payback time of between 8 and 12 years.

The solar cells is the most expensive part of the system - 100-120.000 DKK. A further reduction of the price of solar cells - which is anticipated - will have a major influence of the economy of the IEPB-component.

References

Østergaard Jensen, S., 1990. Results from tests on a Multi-Function Solar Energy Panel. Thermal Insulation Laboratory. Technical University of Denmark. Report no. 213. June 1990. 81 pages.

Østergaard Jensen, S., 1990. Multi-Function Solar Energy Panel. Paper for the Symposium: Building Physics in the Nordic Countries, Trondheim (Norway), 20-22 August 1990. 6 pages.

Østergaard Jensen, S., 1991. Air to water heat exchangers for roof space collectors (in Danish, not yet published). Thermal Insulation Laboratory. Technical University of Denmark