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# Efficiency of a Double Block Cross Flow Balanced Ventilation System with Heat Recovery

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## Summary

In Amstelveen, The Netherlands, an apartment complex of forty two units has been build. Sixteen units are extreme low energy apartments. These apartments are very well isolated and have air tight facades. Moreover, they are equipped with solar collectors for the domestic hot water system, a high efficiency boiler for space heating and additional heating of the domestic hot water, automatic controlled sun shading devices, a balanced ventilation system with heat recovery and an advanced control system that controls the indoor climate, the mechanical ventilation and the sun shades according to the measured indoor temperature and outdoor climate. In the winter the apartments use air from the atrium which is always some degrees higher than the outdoor air. The balanced ventilation system with heat recovery will be discussed in this paper. Before the units are installed in the apartments, one is tested in the laboratory of the Delft University of Technology. Depending on the climatological conditions, the efficiency of the heat recovery unit is between 72.1% to 84.5%. The yield factor, when the recovered heat from the ventilator is also accounted for, is approximately 5% higher, between 78.5% to 88.5%. By an average atrium temperature of 5 $^0$C it is possible to recover approximately 115 m$^3$ gas-equivalent annually from the exhaust air.

## 1. Introduction

In Amstelveen, The Netherlands, an apartment building of forty two units, called 'Urban Villa', has been build, see **figure 1**. Sixteen units (dark coloured) are executed as extreme low energy units according the IEA TASK XIII energy concept, namely an annual energy consumption for end users of not more than 45 kWh.m$^{-2}$. Of this, auxiliary space heating comprises not more than 16 kWh.m$^{-2}$, including electricity demand to drive pumps and ventilators.

The units are very well isolated and have air tight facades. Great care has been taken to avoid cold bridges. To achieve this target, diverse conservation technics, strategies and energy saving appliances [1,2,3] are used, such as: solar collectors for the domestic hot water system and a high efficiency boiler for space heating and additional heating of the domestic hot water, a balanced ventilation system with heat recovery and an advanced control system [4,5] to control the indoor climate (3 individually controlled zones in the apartment), the mechanical ventilation system and the sun shading device according to the measured indoor temperatures and outdoor climate (solar radiation, outdoor air temperature, wind and rain). In the winter the intake air for these 16 low energy units is taken from the atrium. Because of all these measures, the total annual energy consumption is approximately 36.75 kWh.m$^{-2}$.

One of the components that contributes to this extreme low energy consumption is the balanced ventilation system with heat recovery. This system must have a thermal efficiency of at least 80%. A prototype has been tested by the Delft University of Technology [3]. Because the results were very promising, it was decided to use this balanced ventilation system with heat recovery, after some modifications, in this project.

This paper will discuss the test results of the modified heat recovery unit.

## 2. The ventilation system

Because of the very good air tightness of these extreme low energy apartments, a mechanical ventilation system is recommended. To recover the heat from the exhaust air, a balanced ventilation system with heat recovery is used. In the winter the recovered heat from the exhaust air is used to heat up the supply air, that is taken from the atrium. The preheated air is supplied to the living room, both bedrooms and to the kitchen. The exhaust air is taken from the bathroom, toilet, kitchen and the technical room.
In the summer, when the outdoor temperature is higher than 15 $^0$C or the atrium temperature is higher than 17 $^0$C, the supply ventilator is switched off when an outdoor window or the balcony door is opened. The exhaust ventilator is never switched off. The intake air is then supplied by natural means through the outdoor windows or balcony door, while the exhaust is still mechanically.

The ventilation system has 3 positions, low (100 $m^3.h^{-1}$), middle (175 $m^3.h^{-1}$) and high (250 $m^3.h^{-1}$). The high position can be switched on by a switch in the kitchen and in the bathroom; it stays on for 1 hour and then returns to the last position. At day the ventilation system stays in the middle position and at night it returns to the low position.

## 3. The heat recovery unit

The heat recovery unit [6] consists of a double block cross flow plate heat exchanger. The blocks are arranged in series. In front of the inlets of the heat exchanger are air filters. The difference between the prototype and the modified unit is the arrangement of the supply and exhaust ventilators. In the prototype these are placed at the entrance of the flow stream, while in the modified version these are placed at the end, see **figure 2**. As a consequence, in the prototype there exists an over pressure in the heat recovery unit. In the modified version however we get an under pressure in the heat recovery unit. As we will see later, this arrangement will influence the performance of the units.

**Figure 3** shows an open unit of the modified heat recovery system in the test rig. The ventilators and blocks are placed in a plate steel housing with a removable air tight cover. To change the air filters, the cover must first be opened and removed. **Figure 4** shows the arrangement of the boiler and the heat recovery system in the technical room of one of the apartments.

## 4. The thermal efficiency of a cross flow heat exchanger

Schedwill [7] has done research on various cross flow heat exchangers, including cross flow plate heat exchangers. The maximum heat, transferred in a heat exchanger, 💣, is given by:

$$\Phi = \eta_{th} \bullet W_1 \bullet ( \theta_{h\_in} - \theta_{c\_in} ) \qquad (1)$$

with :

$$\eta_{th} = 1 - \frac{W_2}{UA} \bullet \exp^{-\frac{UA}{W_1} - \frac{UA}{W_2}} \bullet \sum_{n=0}^{\infty} \frac{[\frac{UA}{W_1}]^n}{n\,!} \bullet \sum_{p=n+1}^{\infty} (p-n) \bullet \frac{[\frac{UA}{W_2}]^p}{p\,!} \qquad (4)$$

$$W_1 = \phi_{v,1} \bullet \rho \bullet c \qquad (2)$$

$$W_2 = \phi_{v,2} \bullet \rho \bullet c \qquad (3)$$

with:

A = heat transfer area [$m^2$]
c = specific heat [$J.kg^{-1}.K^{-1}$]
U = heat transfer coefficient [$W.m^{-2}.K^1$]
W = heat capacity flow [$W.K^{-1}$]
$W_1$ = the smallest heat capacity flow in the unit [$W.K^{-1}$]
$W_2$ = the highest heat capacity flow in the unit [$W.K^{-1}$]
🗀$_{th}$ = thermal efficiency [-]
🗎$_{c\_in}$ = inlet temperature of the cold medium [$^0C$]
🗎$_{h\_in}$ = inlet temperature of the hot medium [$^0C$]
♦ = specific mass [$kg.m^{-3}$]
💣 = heat transferred [W]
☠$_{v,1}$ ☠$_{v,2}$ = volume flows [$m^3.s^{-1}$]

As can be seen from (2), the expression for the thermal efficiency of a double block cross flow plate heat exchanger is very complex and difficult to grasp in a single number. It is common to denote the thermal efficiency of a cross flow heat exchanger graphically as function of two of the dimensionless parameters $UA/W_1$, $UA/W_2$ or $W_1/W_2$ [7].

When two cross flow heat exchangers with the same thermal efficiency 🗀$_1$ are arranged in series, the total thermal efficiency 🗀$_2$ of the double block heat exchanger can be denoted in the individual efficiencies 🗀$_1$ as [3] :

$$\eta_2 = \frac{2 \bullet \eta_1}{1 + \eta_1} \qquad (5)$$

One block measures 0.3*0.3*0.3 m and consists of 102 steel plates of $2.0*10^{-4}$ m thick. The total heat transfer area is thus A = 9.1 m$^2$. With an air passage between two plates of approximately $2.75*10^{-3}$ m, the total flow area per side becomes approximately $4.125*10^{-2}$ m$^2$. For a maximum air flow of 250 m$^3$.h$^{-1}$, the air speed in the heat exchanger is 1.68 m.s$^{-1}$. With a hydraulic diameter (4*area/circumference) of one air passage of $5.45*10^{-3}$ m and a kinematic viscosity of air of $1.5*10^{-5}$ m$^2$.s$^{-1}$, the calculated Reynolds number is Re = 610. The transition region from laminar to turbulent is Re = 2300, so it is save to assume a laminar flow through out the whole ventilation range. In this laminar region the heat transfer coefficient is U = 19 [W.m$^{-2}$.K$^{-1}$]. Because the supply and the exhaust air flow rates are the same, so $W_1=W_2$ and thus the thermal efficiency of one block can be determined with equation (2). This is shown in **figure 5** as the lower graph as function of UA/W. The thermal efficiency of the double block cross flow heat exchanger can finally be determined with equation (5). This is shown in **figure 5** as the upper graph. This last graph characterizes the theoretical thermal efficiency of the double block heat recovery unit as used in Urban Villa.

## 5. The experimentally determined thermal efficiency and yield factor of the double block cross flow heat recovery unit

From the experiments the thermal efficiency of the double block cross flow heat recovery unit is calculated according equation (6) (see also figure 2 for the used number notations):

$$\eta_{th} = \frac{\phi_{v,s} \bullet (\theta_3 - \theta_1)}{\phi_{v,o} \bullet (\theta_5 - \theta_1)} \qquad (6)$$

with $\theta_3$ is the temperature of the supply air just after the heat exchangers, but before the supply ventilator. When the heat addition of the supply ventilator is also taken into account, then this is called **the yield factor** and denoted by $\eta'_{th}$. The yield factor can be found with equation (6) by substituting $\theta_3$ with $\theta_4$ (air temperature after the ventilator):

$$\eta'_{th} = \frac{\phi_{v,s} \bullet (\theta_4 - \theta_1)}{\phi_{v,o} \bullet (\theta_5 - \theta_1)} \qquad (7)$$

with:

$\eta_{th}$ = thermal efficiency [-]

$\eta'_{th}$ = yield factor [-]

$\theta_1, \theta_{1a}$ = supply air temperature [$^0$C]

$\theta_3$ = supply air temperature after the heat exchanger [$^0$C]

$\theta_4$ = supply air temperature after the intake ventilator [$^0$C]

$\theta_5, \theta_{5a}$ = exhaust air temperature at the inlet [$^0$C]

$\phi_{v,o}$ = exhaust air flow [m$^3$.s$^{-1}$]

$\phi_{v,s}$ = supply air flow [m$^3$.s$^{-1}$]

## 6. Internal and external leaks

Air leaks can occur in the heat recovery unit. We distinguish between internal and external leaks. The internal leaks occur between the supply and the exhaust side vice versa and the external leaks from the outside to the inside of the unit vice versa.

When air leaks from the exhaust to the supply side, the thermal efficiency will increase, because the cold intake air is mixed with the warm exhaust air. But the air quality decreases, because the exhaust air (included from the kitchen and the toilet) is recirculated back into the apartment. This is not acceptable under all circumstances.

When on the other hand air leaks from the supply to the exhaust side, the thermal efficiency will decrease, because the supply air flow will decrease, but this doesn't influence the air quality.

An external leak means that heated air from the technical room will be mixed with either the supply or exhaust air. When it is mixed with the supply air, the thermal efficiency of the unit will be increased and rather clean air is recirculated; the air quality is not much affected. When the leak is to the exhaust side, more conditioned air is exhausted than necessary and this increase the heating requirement. Put all together, it is better to prevent air leaks in the heat recovery unit.

## 7. The experiments

The experiments include temperature and air flow measurements in the heat recovery unit and measuring the electric power at low, medium and high ventilation rates. In **figure 2** the location of the thermocouples is given. To determine the leaks, the air flows at the input and output of the supply and exhaust sides of the heat exchanger and at location 1, 4, 5, and 8 of the unit are measured.

The experiments are performed at low, medium and high ventilation rates with -5, 0, 5 and 10 $^0$C atrium temperatures. The indoor temperature is kept constant at 20 $^0$C.

## 8. Results of the experiments

Table I shows the air flows measured at the entrance and outlet of the supply and exhaust sides. While the supply air flow increases over the whole ventilation range, the exhaust air flow decreases in the low and medium range. Only for the highest range it shows a small increase. A positive difference means a leak into and a negative difference a leak out of the side in question. At the low and medium range the supply air increases more than the exhaust air decreases, so this means, that there is also an external leak. This external leak is more than the internal leak. The internal leaks decrease in the upper range. The external leaks increase with the speed. This is caused by the deeper under pressure in the unit when the ventilators are running in the maximum range. The measured supply and exhaust air flow rates are over the whole ventilation range higher than the nominal rated flows.

**Table I** **Air flows and leaks at various ventilator speeds**

| **Error! Bookmark not defined.**🗀$_{v,nom}$ 3.6*$10^3$ * [$m^3.s^{-1}$] | | Supply side | Exhaust side | leaks | |
|---|---|---|---|---|---|
| | | 3.6*$10^3$*[.$m^3 s^{-1}$ ] | | internal | external |
| Low 100 | in | 134 | 137 | | |
| | out | 148 | 132 | | |
| | difference | +14 | -5 | 5 | 9 |
| Medium 175 | in | 214 | 209 | | |
| | out | 231 | 205 | | |
| | difference | +17 | -4 | 4 | 13 |
| High 250 | in | 325 | 293 | | |
| | out | 344 | 295 | | |
| | difference | +19 | +2 | - | 21 |

The internal and the external leaks influence the real thermal efficiencies and yield factors. The correction is done in the next paragraph.

Correction of the thermal efficiency and of the yield factor

Because of the leakage from exhaust to supply side, the cold supply air is mixed with air from the exhaust side and from the technical room. This results in increasing the thermal efficiency. To obtain the real thermal efficiency, the air temperature after the heat exchanger, 🖹$_3$, must be corrected. The corrected air temperature, 🖹$_3$', is determined by:

$$\theta_{3'} = \frac{\phi_{v,3} \bullet \theta_3 - \phi_{v,leak} \bullet \theta_5}{\phi_{v,1}} \tag{8}$$

with:

🖹$_3$ = intake air temperature after the heat exchanger
🖹$_3$' = corrected air temperature after the heat exchanger
🖹$_5$ = exhaust air temperature at the entrance
☠$_{v,1}$ = supply air flow at the entrance
☠$_{v,3}$ = supply air flow from the heat exchangers
☠$_{v,leak}$ = leak to the intake compartment

The corrected thermal efficiency 🗀$_{th}$ is found by substituting 🖹$_3$ in equation (5) with 🖹$_3$' from equation (8). On the same manner the corrected yield factor C$_{th}$ is found by correcting 🖹$_4$ on the same manner as 🖹$_3$ with equation (8).

In **Figure 6** the thermal efficiency, □$_{th}$, and the yield factor, Ġ$_{th}$, of the heat recovery unit are shown. As has been said before, the difference between the thermal efficiency and the yield factor is the recovered heat from the ventilator. It seems, that this recovered heat increases the efficiency of the heat recovery unit by approximately 5%.

## 9. The yield of the heat recovery unit

The yield of the heat recovery unit can be determined by equation (1) by substituting $W_1$ with equation (2) and using the specific properties of air. This is given in equation (9). We distinguish between yield exclusive the recovered heat from the ventilator, 💣, and the yield inclusive the recovered heat from the ventilator, 💣'.

$$\Phi = \eta_{th} \bullet \phi_{v,o} \bullet ( \theta_5 - \theta_1 ) \bullet \rho \bullet c \qquad \textbf{(9)}$$

with:

💣 = yield of the heat recovery unit, excl. ventilator [W]

💣' = yield of the heat recovery unit, incl. ventilator [W]

□$_{th}$ = thermal efficiency of the heat recovery unit [-]

□'$_{th}$ = yield factor of the heat recovery unit [-]

☠$_{v,o}$ = exhaust air, Table 1, column 4, row 'in' [$m^3.s^{-1}$]

📄$_5$ = indoor temperature, constant at 20 °C [°C]

📄$_1$ = outdoor/atrium temperature, resp. -5, 0, 5 en 10 °C [°C]

🖓 = specific mass of air 1.2 [$kg.m^{-3}$]

c = specific heat of air 1000 [$J.kg^{-1}.K^{-1}$]

In **figure 7** and **figure 8** are shown the yields of the heat recovery unit with (full line) and without (broken line) the recovered heat from the ventilator as function of respectively the outdoor temperature and the air flow.
From the electrical power for the ventilators of 56, 97 and 176 W for respectively the low, medium and high speed, an average of 39 W (69.6%), 58 W (59.8%) and 76 W (43%) is recovered and returned as heating energy in the supply air.

## 10 The contribution of the heat recovery unit to space heating

As has been said in the introduction, the apartments of Urban Villa are very good isolated and the connections are air tight. So, in the winter, most of the ventilation air is obtained through the balanced ventilation system with heat recovery.

Assuming a daily use of the ventilation system of 18 hours in low, 5 hours in medium and 1 hour in high speed (bath, cooking, toilet) in the winter season (October - April), the electricity used for the supply and exhaust ventilators of the balanced ventilation system is approximately 350 kWh, whether heat recovery is used or not.
The gas required for space heating by a mean indoor temperature of 20 °C and outdoor temperature (atrium temperature) of 5 °C is approximately 140 $m^3$ gas.

When heat recovery is used, the supply air temperature is increased to 17.3 and 16.8 °C in the medium and high range respectively. Consequently only approximately 25 $m^3$ gas is required for additional heating. This means, that with heat recovery, approximately 140 - 25 = 115 m$^3$ of gas is saved in the heating season for space heating. With a gas price of approximately f 0.50 in the Netherlands (1994) this is a saving of f 57.50 a year.

Because of the high yield factor of the heat recovery unit, supply air of -5 °C will be heated to 15 °C before it is introduced into the apartment, so there is no danger of draught.

## 11. The theoretical versus the experimental determined thermal efficiency of the heat recovery unit

In paragraph 4 a heat transfer coefficient of U = 19 W.m$^{-2}$.K$^{-1}$ is has been found for the heat exchangers of the heat recovery unit.

With (2) the heat capacity flow W can be determined for the low, medium and high range; it is respectively 44.67, 70 and 108.3 [W.K$^{-1}$].

Now the parameter UA/W can be determined, this is respectively 3.8, 2.4 and 1.6. Using **figure 5** we can find the theoretical thermal efficiency, ☐$_{theor}$, of the heat recovery unit; this is respectively 82%, 79% and 74%.

As can be seen from **figure 6**, the experimental thermal efficiency, ☐$_{exp}$ depends very much on the outdoor/atrium temperature. In **Table II** the theoretical and the experimental thermal efficiencies, ☐$_{th}$, and the yield factors, ☪$_{th}$, for the range -5 °C to 10 °C are given. It seems. that the theoretical efficiencies are good averages of the experimental values.

**Table II** **The theoretical and the experimental thermal efficiency**

| **Error! Bookmark not defined .☠** | 3.6*10$^3$ [m$^3$.s$^{-1}$] | Low [134] | Medium [214] | High [325] |
|---|---|---|---|---|
| UA/W | [-] | 3,8 | 2,4 | 1,6 |
| ☐$_{theor}$ | [%] | 82 | 79 | 74 |
| ☐$_{exp}$ | [%] | 84.5 - 77.1 | 81.5 - 74.9 | 77.4- 72.1 |
| ☪$_{exp}$ | [%] | 88.5 - 82.5 | 84.5 - 82.5 | 82.5- 78.5 |

## 12 Discussion and conclusion

1. Present-day houses are very good isolated and great care is taken to prevent air infiltration through cracks in the walls and connections between wall and window frame. Because of this a mechanical ventilation system is recommended to maintain a good indoor air quality. By using a balanced ventilation system with heat recovery sufficient heat from the exhaust air can be recovered so that the annual gas consumption for heating the ventilation air is only 25 m$^3$.

2. Because of the yield factor of 88.5% in low speed and 84.5% in medium speed, intake air from the atrium of 5 $^0$C will be heated to 17.3 $^0$C and 16.8 $^0$C with an indoor temperature of 20 $^0$C. These air temperatures are high enough to prevent draught. At the highest speed the yield factor drops to 82.5 and the intake air temperature becomes 15.25 $^0$C.

3. Leaks, particularly from the exhaust to the intake compartment, must be prevented under all circumstances. Especially in the new units with the position of the ventilators at the end of the intake and exhaust path, great care must be taken to prevent leaks.

4. To change the air filters the air tight cover must be removed. Frequent opening and closing of this cover by non-technical people will sooner of later result in leaks. This can be prevented by placing the filters on the outside of the housing.

5. The yield factor, with the recovered heat from the ventilators included, is a better characterization for heat recovery unit than the thermal efficiency that characterizes only the heat exchangers.

6. At this moment a heat recovery system is not yet economical because of the low energy prices.

## Acknowledgement

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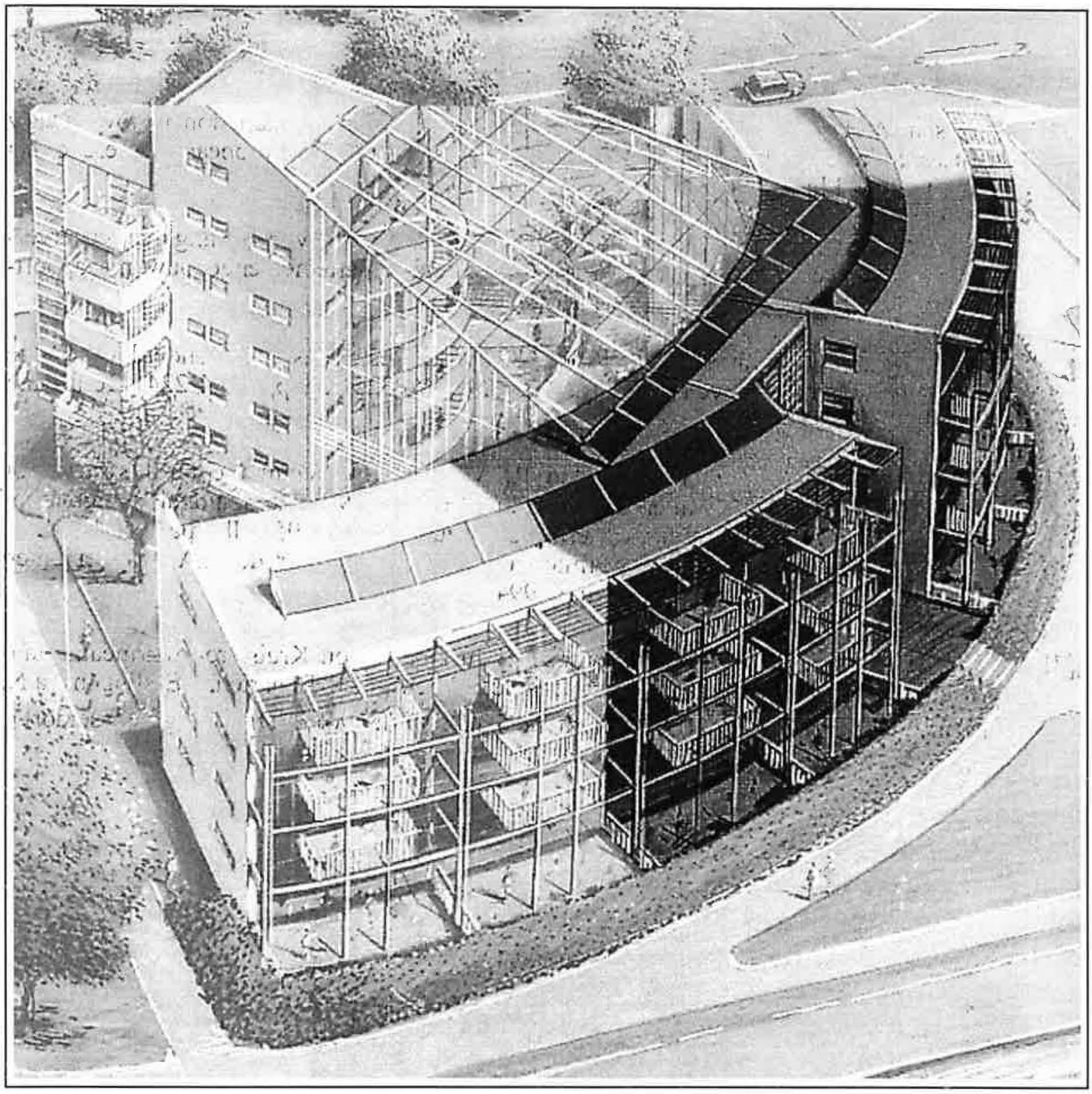

***Figure 1*** *The apartment complex "Urban Villa" in Amstelveen, The Netherlands*

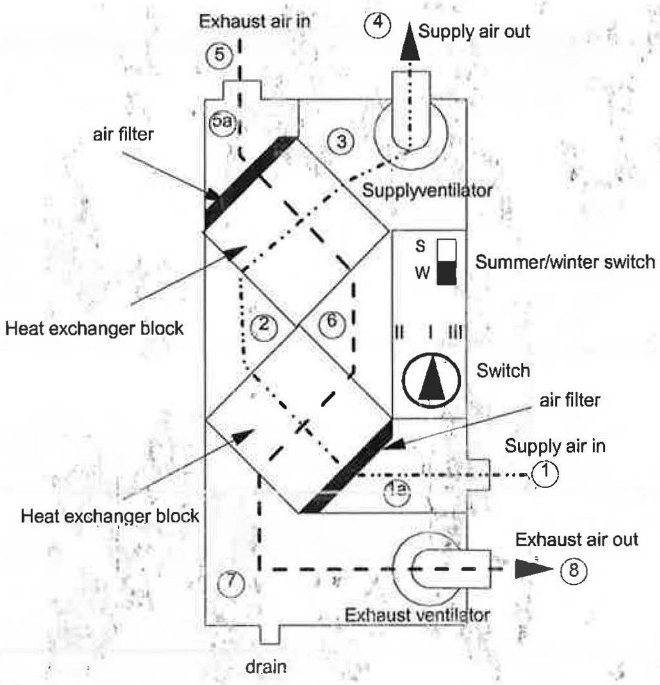

**Figure 2**

*Schematic view of the heat recovery unit*

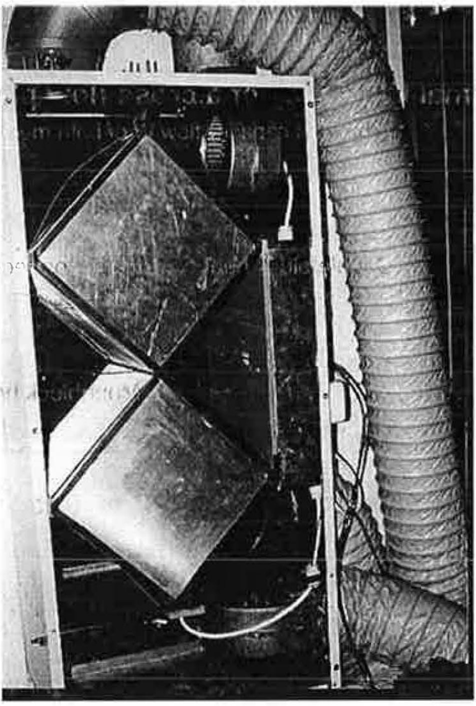

***Figure 3*** *The Heat Recovery Unit with the cover removed*

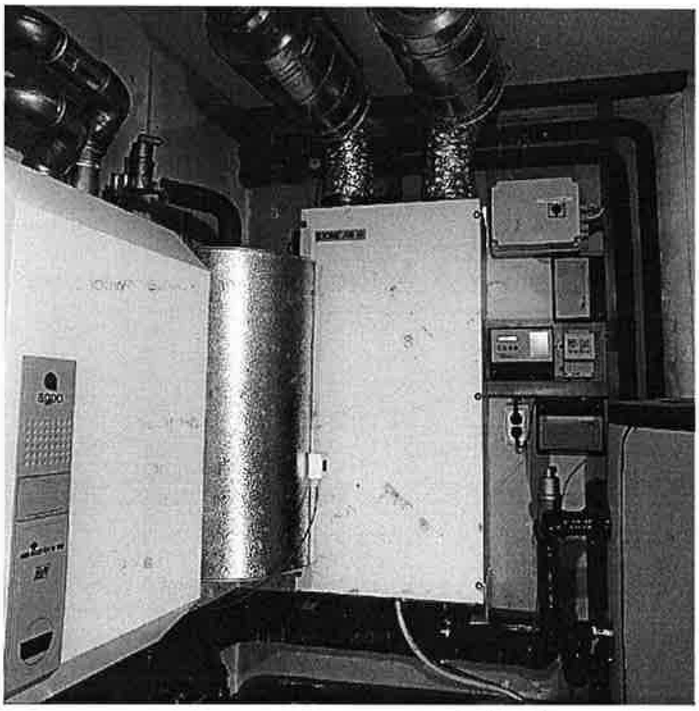

*Figure 4* *View in the technical room*

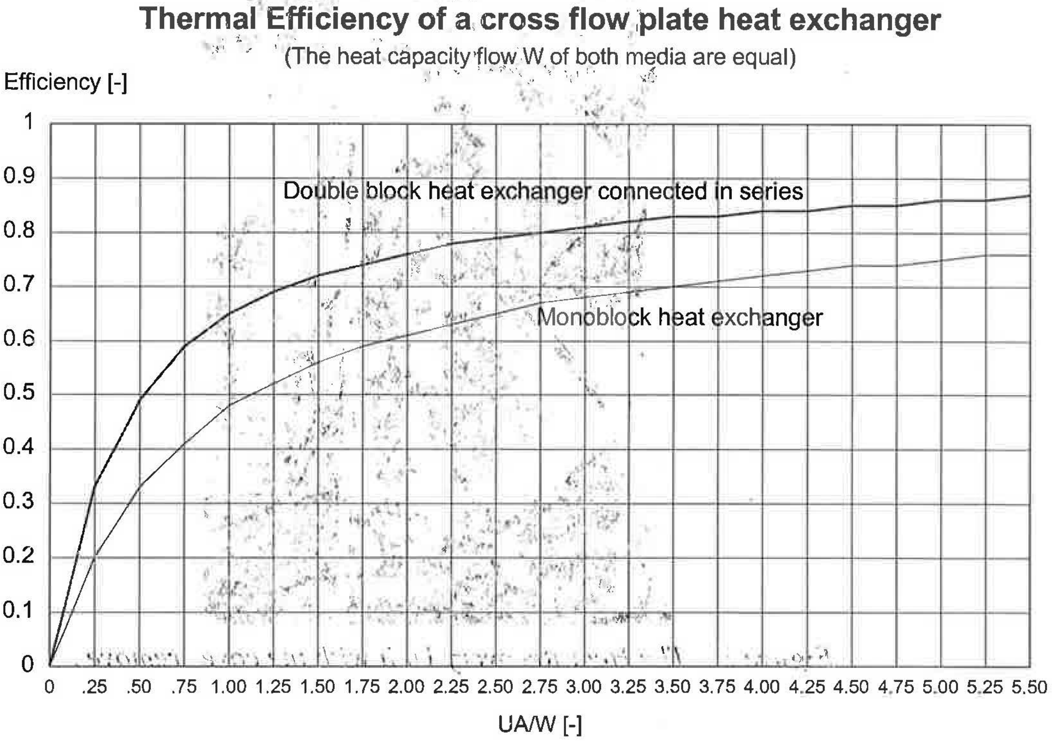

***Figure 5*** *The thermal efficiency of a mono- and double block cross flow heat exchanger*

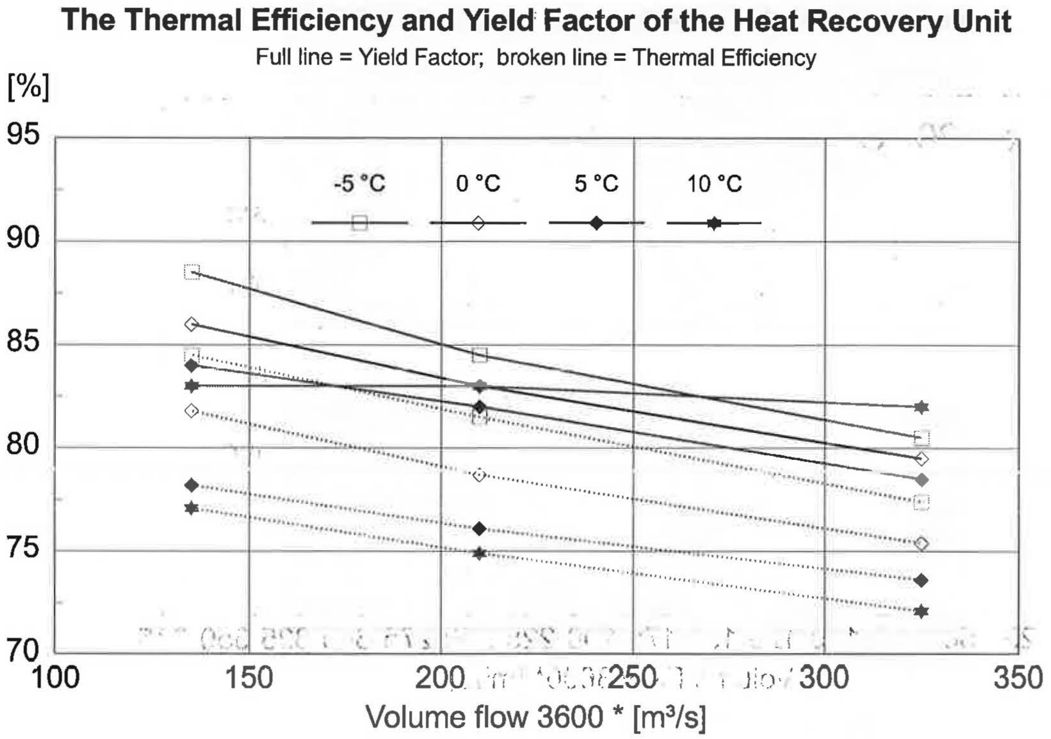

*Figure 6* *The Thermal Efficiency and Yield Factor of the Heat Recovery Unit*

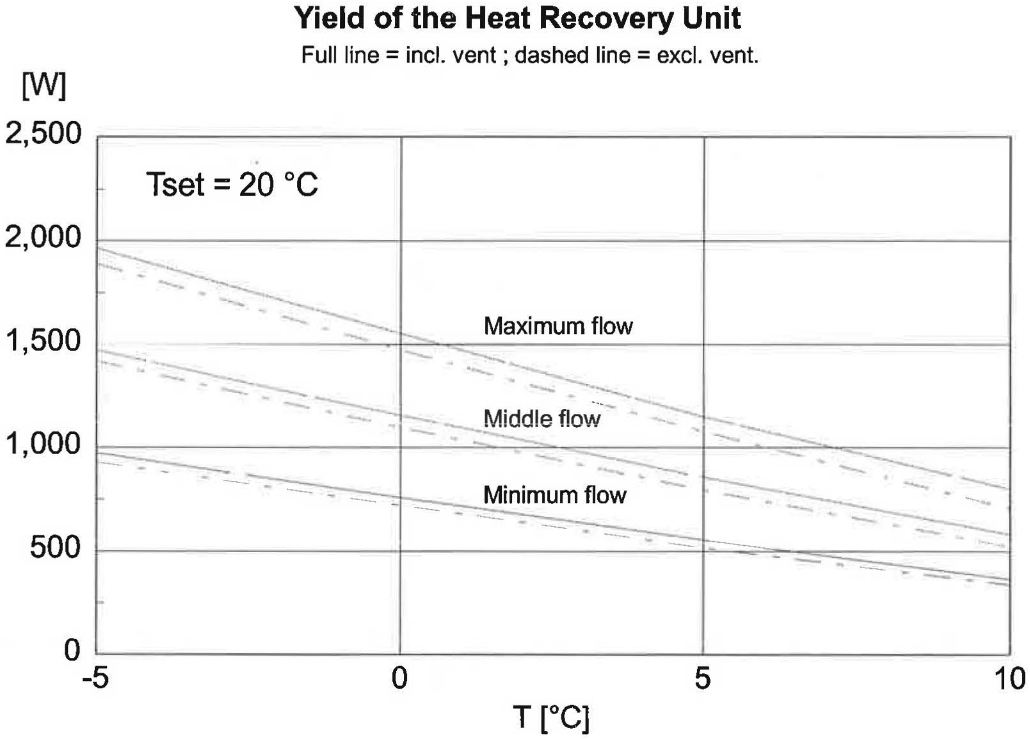

*Figure 7* *The Yield of the Heat Recovery Unit as Function of the outdoor temperature*

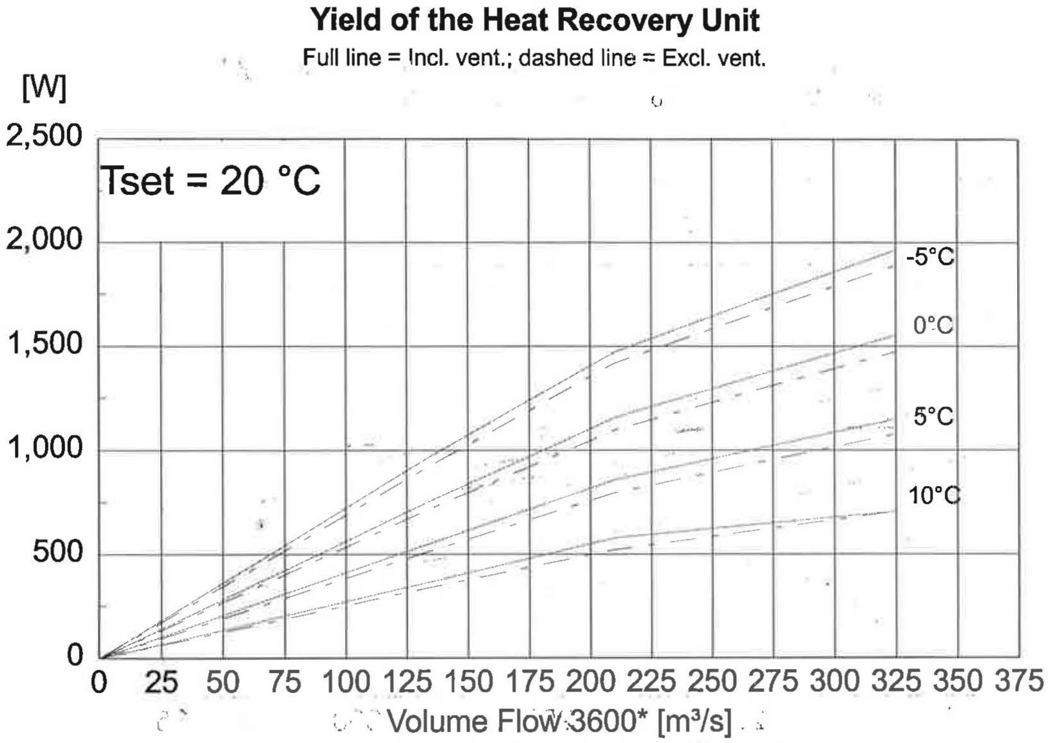

***Figure 8*** *The Yield of the Heat Recovery Unit as Function of the flow*