LONG TERM MONITORING OF RESIDENTIAL HEAT RECOVERY VENTILATION WITH GROUND HEAT EXCHANGE

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ABSTRACT
The monitoring of a demand controlled heat recovery ventilation system with ground heat exchange in a zero-energy building in Groenlo, The Netherlands, revealed interesting practical insights.

A healthy indoor climate can be obtained with a high comfort in terms of CO_2 levels and supply air temperatures. The CO_2 level stays well within the comfortable range in the living room and three bed rooms (parents, child, and guests), thanks to the demand controlled ventilation. Supply air temperatures are in the comfortable range thanks to the heat recovery in combination with the ground heat exchange by an earth pipe. This is shown for ambient temperatures between -8°C and +33°C.

The energy efficient behaviour is proven by the avoided heating load of 3465 kWh and free cooling of 1052 kWh during a full year. The observed seasonal performance factor SPF is 17 for the avoided heating and 8 for the free cooling. The thermal efficiency based on the supply air temperature is observed to be as high as 91% for a slightly unbalanced air flow. When this is mathematically corrected, the thermal efficiency would have been 97% for a perfect balance between supply and return air flow.

KEYWORDS
Indoor air quality (IAQ), residential ventilation, heat recovery, ground heat exchange, passive cooling, monitoring, CO_2, recovery efficiency, demand control

INTRODUCTION
This article reports the results of a full year monitoring of a zero-energy residential building in Groenlo, the Netherlands. The ventilation system in this building is a demand controlled heat recovery ventilation system in combination with ground heat exchange in the form of an earth pipe. The results of the monitoring show that the ventilation system is highly energy efficient and provides a healthy and comfortable indoor climate.

THE BUILDING
The monitored building displayed in fig. 1 has been built according to the passive house standards. In general terms, the house has a compact, well insulated envelope and south oriented windows with triple glazing. Photovoltaic panels and solar thermal collectors on the roof provide electricity and hot tap water during sunny weather. A heat pump coupled to a vertical bore hole is providing heating and cooling via a floor distribution system. Details of the house can be found in [1] and [2].

Figure 1. The monitored building in Groenlo, The Netherlands.

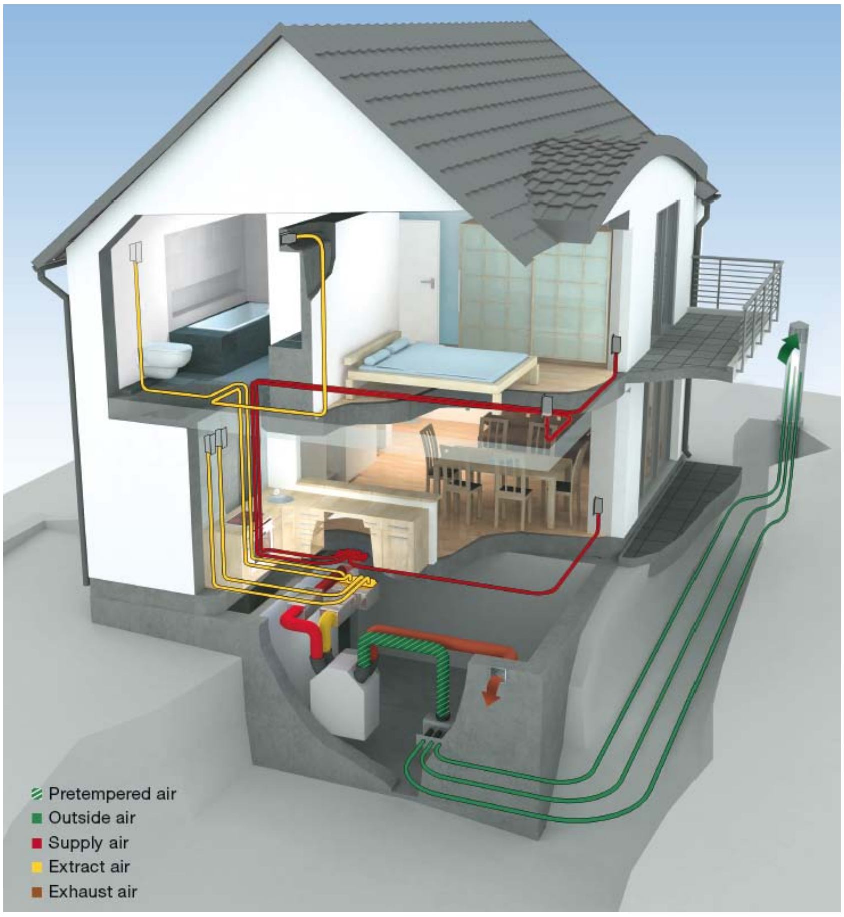

Figure 2. Representation of the ventilation system.

THE VENTILATION SYSTEM

A heat recovery unit is bringing fresh outdoor air into the building and is removing stale air from the building (see fig. 2). The heat from the extract air is recovered and returned back into the fresh air for energy efficient ventilation. The standard ventilation volume is 160 m^3/h. In a house with a volume of 840 m^3 this corresponds to a ventilation rate of around 0.2 h^{-1}.

The outdoor air is supplied to the individual rooms by 7 individual flexible circular ducts. Four of them lead to low induction grilles near the floor of the bedrooms (parents, child and guests) and an office room, all situated on the ground floor. The rest leads to the first floor to the living room. Extract air is extracted from the living room, the loft, the bathroom and the toilets via 7 return ducts. Supply air as well as return air are distributed and collected respectively via sound attenuators, one in the extract air stream and two in the supply air stream. The kitchen is ventilated by a separate HRU which is not subject of the monitoring project.

The manual setting of the ventilation volume (standard position 1; 160 m^3/h) is increased automatically by a demand control based on 4 individual CO_2 sensors in the living room and the bedrooms (parents, child and guests). If one of the CO_2 levels is above a pre-set threshold level, a signal is brought to the HRU to increase the air volume.

Ground heat is provided by an earth pipe. The earth pipe is 50 m long with a diameter of 200 mm and a mean depth of 2.5 m. It is buried into the earth at a slope to remove any possible condensation in the pipe. An air damper is installed in the fresh air duct upstream of the HRU. The HRU controls the damper to decide whether outdoor air is brought into the building directly from outside (north façade) or via the earth pipe (inlet see foreground in fig. 1). Note: fig. 2 shows a slightly different version with 3 parallel and shorter earth pipes without a damper installed.

THE MONITORING

The relevant parameters of the ventilation system have been collected at an interval of 1 minute by a laptop connected to the HRU. The collected data is sent weekly by the resident accompanied by any relevant feedback. The data is transformed into hourly values and analysed in the form of so-called carpet plots, duration graphs, correlation diagrams or bar charts. This report gives the results of a full year starting in February 2011 until February 2012. An intermediate report for a half year period can be found in [3].

COMFORTABLE CO_2 LEVELS

The comfort in the house is assessed by the CO_2 levels in the living room, the master bedroom (2 parents), the child's bedroom and the guest bedroom. The threshold level for the living room was set at 800 ppm and for the bedrooms at 1000 ppm.

As expected, the hourly CO_2 values showed an increased CO_2 level when the rooms were occupied. As an example, fig. 3 shows the CO_2 levels in the child's bedroom for the period February to May 2011. During the day, CO_2 levels are close to the natural background level of 400 ppm while during the night they were in the range 800 – 1000 ppm. When the CO_2 level exceeded the threshold level of 1000 ppm, the ventilation was increased automatically by the HRU to maintain the CO_2 level within a healthy and comfortable range.

From mid-April on, there is a generally lower CO_2 level in all of the rooms resulting from window ventilation used in this period of higher solar irradiation on the south façade.

Another observation is that the CO_2 level during the night was generally higher in the child's bedroom (occupied by one child) than in the master bedroom (occupied by two adults). The reason for this is that the child sleeps with the door closed and the parents sleep with the door open. An open bedroom door results in an exchange of the air in the bedroom (with CO_2

source) with the air in the hallway (without CO_2 source). This pattern was confirmed by CO_2 levels above normal when the master bedroom door was closed occasionally.

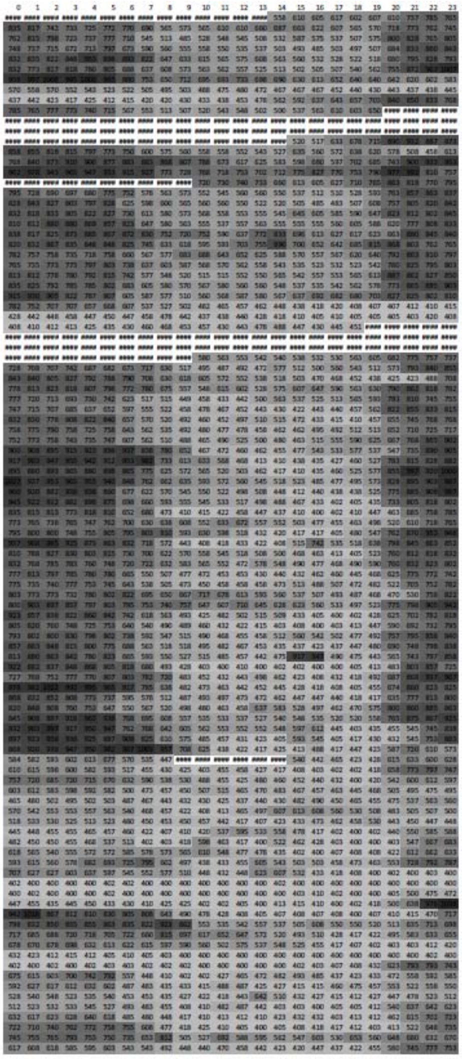

Figure 3. Carpet plot of CO_2 level in the child's bedroom. Rows indicate days from Feb 5th (top row) to May 16th (bottom row). Columns indicate hour of day from 0:00 (left column) to 24:00 (right column). Grey shades indicate CO_2 level ranging from 400 ppm (grey) to 1200 ppm (black), and missing data (white). Note: black represents a CO_2 value that is still below the Dutch guideline values!

The observation of lower CO_2 levels with the door open is confirmed by theoretical calculations. The natural exchange of air by temperature differences between bedroom and hallway can be calculated as 370 m^3/h for a door of 1 m wide and 2 m high with a temperature difference of 1 °C! This is roughly 6 times more than the amount of fresh air of 58 m^3/h provided by the HRU on the maximal level. This means that an open door leads to 6 times faster dilution of CO_2 when compared to a closed door. Note that in case of an open door the CO_2 loaded air is replaced by air from the hallway with unknown air quality, while the HRU ensures the necessary amount of fresh air from outside.

A duration graph of CO_2 levels is given in fig. 4. The uncomfortable level of 1200 ppm is exceeded extremely rare (densely occupied bedroom with closed door). Again, one can see higher CO_2 levels in the child's room than the master bed room during the nights. The CO_2 level of 1200 ppm has never been exceeded in the living room and the child's bedroom. In the master bedroom and the guest bedroom, 1200 ppm has been exceeded only 0.1 % (8 hrs) and 0.2% (16 hrs) of the time, respectively.

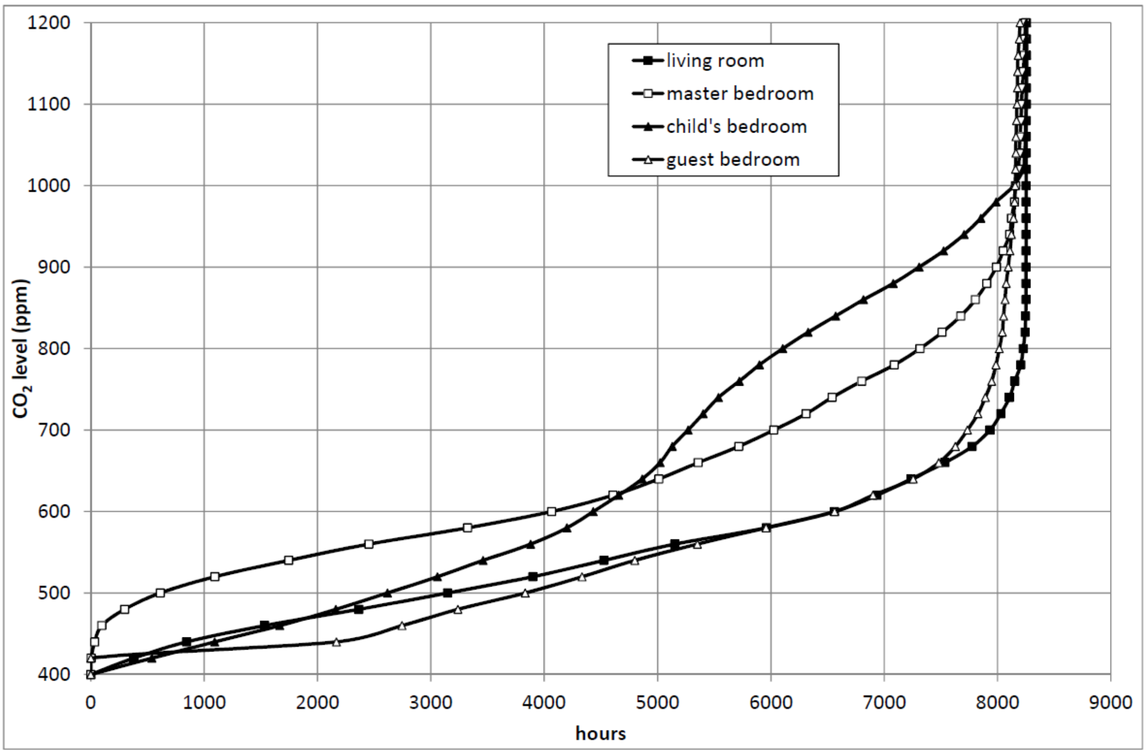

Figure 4. Duration graph of CO_2 levels in living room, master bedroom, child's bedroom and guest bedroom.

COMFORTABLE TEMPERATURES

Throughout the year, the temperature of the earth at 2.5 m depth is much less varying than the outside air temperature. Therefore, the earth can be used for preheating incoming outdoor air in winter and precooling it in summer. In winter, the temperature of the earth is generally higher than the outside air temperature. Fig. 5 shows that the preheated air (at the exit of the earth pipe) is between 8 and 12°C for outside temperatures between -5 and 10°C. In summer, the temperature of the earth is generally lower than the outside air. Fig. 5 shows that the precooled air (at the exit of the earth pipe) is between 12 and 17°C for outside temperatures between 16 and 33°C. For mild outside temperatures between 10 and 16°C the ground heat exchange is switched off by controlling an air valve; outdoor air is taken into the house directly from the north façade (not via earth pipe).

The advantages of the ground heat exchange are the following. In winter, it ensures frost-free operation of the heat exchanger in the HRU, without the need for an electrical anti-freeze heating element. In summer, it decreases the temperature of the outdoor air to a level below the inside temperature, so that free cooling is used for the whole summer period, and not only during cool nights. The extra fan power to draw the air through the earth pipe is negligible (approximately 3 W).

In winter, the (preheated) outdoor air is entering the HRU where it is efficiently heated by the return air in the heat exchanger. Fig. 6 shows that ventilation air is supplied to living room and bedrooms with a comfortable temperature of 18°C in winter even at very low outside temperatures[1]. Without heat recovery, ventilation air would enter the rooms with a temperature equal to outside which would result in uncomfortable draughts.

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[1] some hours with supply temperature below 18°C are situations with the central heating switched off during absence

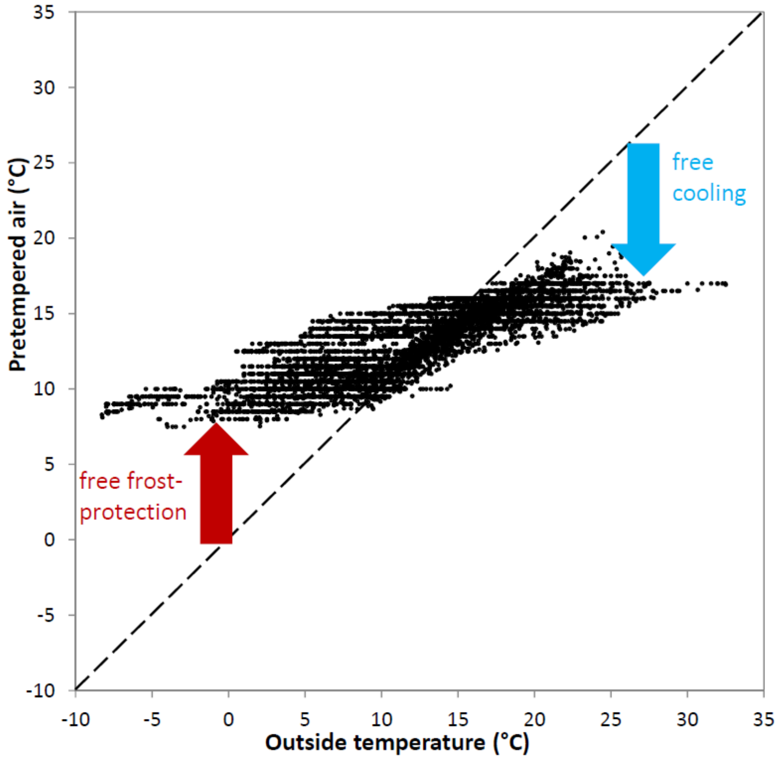

Figure 5. Hourly values of outdoor air entering the house. Ground heat exchange ensures frost protection of the HRU in winter and free cooling for the house in summer.

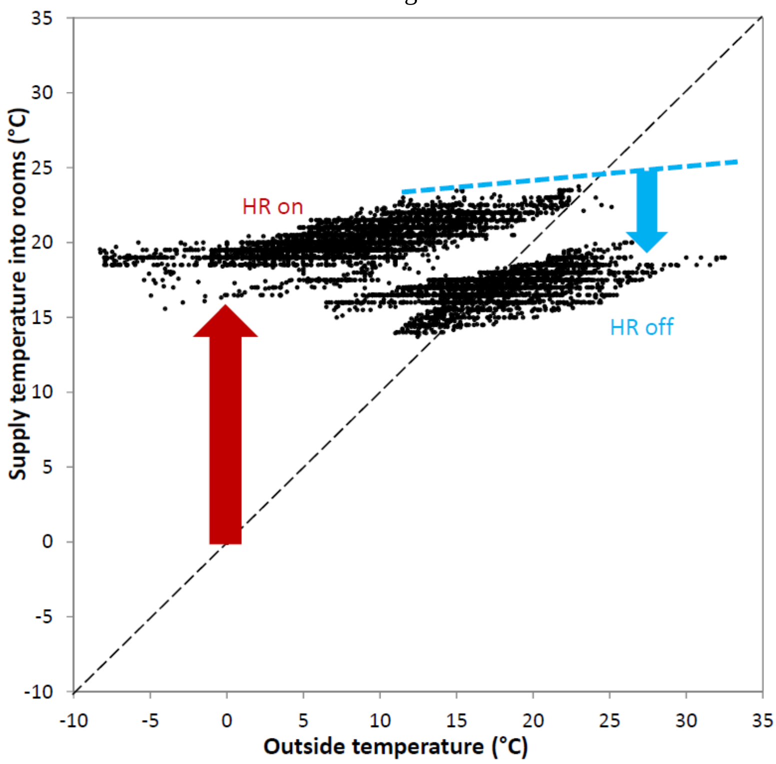

Figure 6. Hourly values of supply air temperature entering the rooms with and without heat recovery (HR on, and HR off). Upward arrow indicates avoided heating and downward arrow indicates free cooling compared to indoor temperature.

For outdoor temperatures above 13°C, the heat recovery is switched off when cooling is both requested and available. This occurs when both of the following conditions are true:

- Actual indoor temperature is above the setting of the comfort temperature (here: 21°C)
- Actual pretempered air temperature is lower than actual indoor temperature.

The heat recovery is switched off by bypassing the heat exchanger in the HRU. Outdoor air is transported directly (without heat recovery) to the rooms. This results in free cooling of the house as the supply temperature is always below the actual indoor temperature. The monitoring shows that the supply temperature is always below 20°C. As the ventilation air flow rate is not large (160 m^3/h), the free cooling cannot be compared with air conditioning equipment, but it raises the comfort and reduces the cooling load of the building.

ENERGY EFFICIENT VENTILATION

The benefits of heat recovery ventilation with ground heat exchange are expressed in terms of avoided heating and free cooling.

With heat recovery switched on, the avoided heating load (or recovered heat) reflects the fact that, thanks to the HRU, the central heating system does not have to heat cold outdoor air to the desired indoor temperature (see upward arrow in fig. 6). The exact amount can be calculated using the actual ventilation flow rate and the actual difference between supply air temperature and outdoor air temperature.

With heat recovery switched off, the free cooling reflects the fact that the indoor air is cooled by the incoming (lower) supply air temperature (see downward arrow in fig. 6). The exact amount can be calculated using the actual ventilation flow rate and the actual difference between indoor air temperature and supply air temperature.

Fig. 7 shows cumulative avoided heating load and free cooling per week during the monitoring period. The energy benefits have been obtained at the expense of the electrical consumption of the fans in the HRU, which consume only 33 W at 160 m^3/h thanks to the low resistance of the flexible air distribution system.

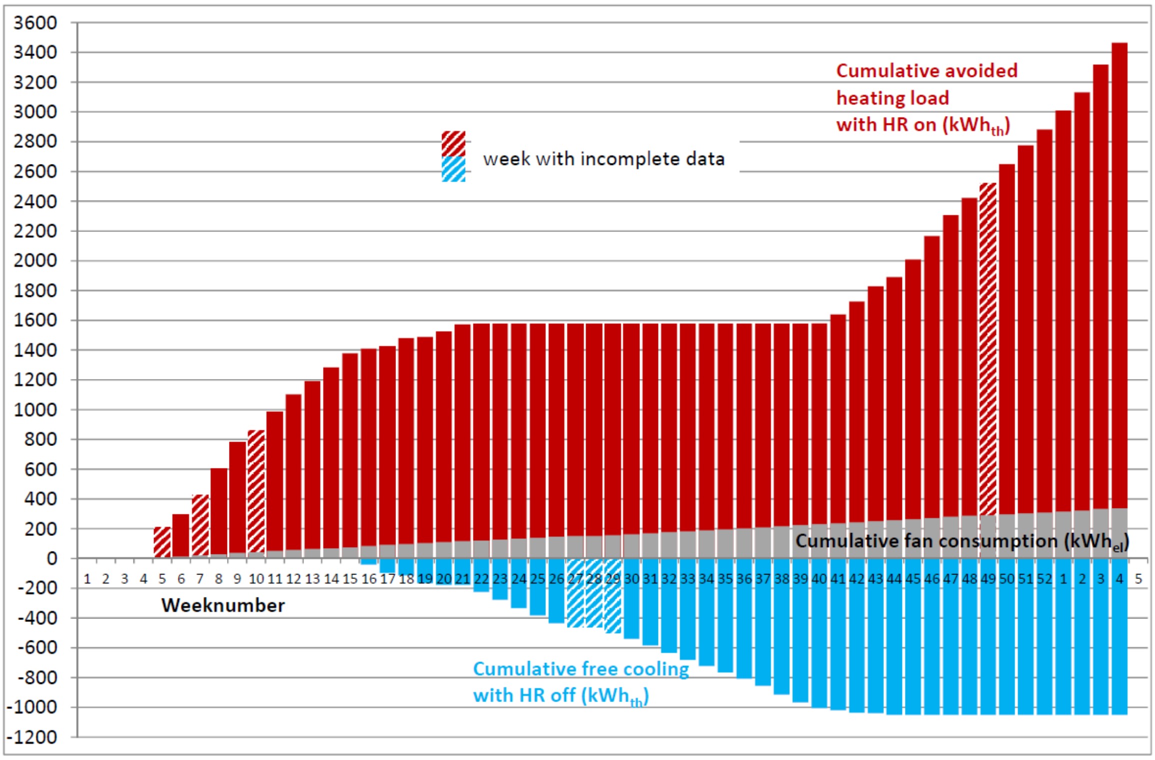

Figure 7. Cumulative sums for avoided heating load (above horizontal axis), free cooling load (below horizontal axis) and fan electricity consumption (above horizontal axis) from week 4 in 2011 to week 4 in 2012.

Table 1 shows a summary of values for the reported period February 2011 until February 2012. The seasonal performance factor SPF for avoided heating (or free cooling) is given by the ratio between avoided heating load (or free cooling load) and the electricity consumption of the fans during hours when the bypass was closed (or open). The observed SPF for avoided heating corresponds reasonably well with an SPF of 22 for the expected gain of a heat recovery system using comparable climate data of Milan, Italy from [4].

	Full year	Electrical consumption of fans during season	Seasonal Performance Factor SPF
Avoided heating load	3465 kWh	199 kWh	17
Free cooling load	1052 kWh	137 kWh	8

Table 1. Annual energy benefit of heat recovery ventilation and seasonal performance factors.

THERMAL EFFICIENCY OF HEAT RECOVERY IN PRACTICE

The thermal efficiency is defined as the ratio between outdoor air temperature increase and maximal temperature increase $(T_{supply\ air}-T_{fresh\ air})/(T_{return\ air}-T_{fresh\ air})$. When ground heat exchange is used, the outdoor air temperature in this formula is the preheated or precooled outdoor air temperature.

The thermal efficiency of an HRU is dependent on a lot of variables, among which ventilation flow rate and mass balance between supply air and extract air are dominant. Fig. 8 shows practical efficiency as a function of fan percentage. The HRU is most frequently in position 1 (fan percentage 35%). Fan positions 2, 3 and absent can also be discerned. Intermediate fan percentages occur when the CO_2 demand control increases fan percentage gradually.

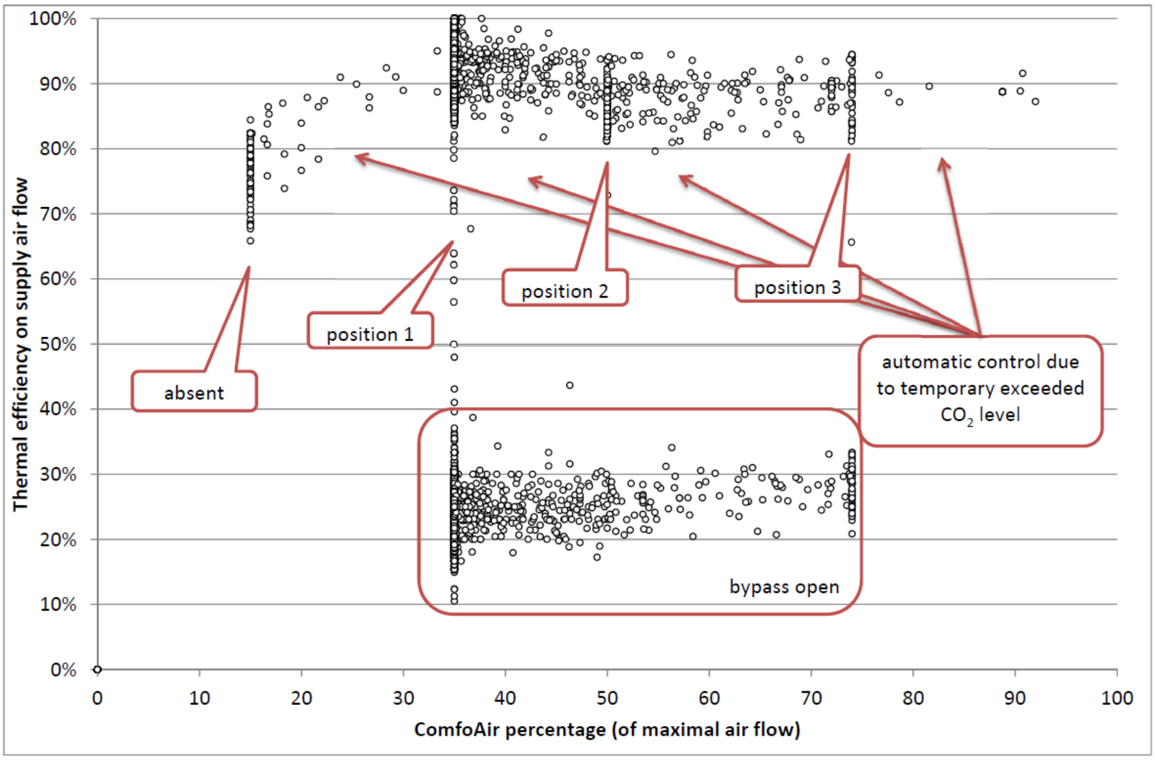

Figure 8. Thermal efficiency of HRU as a function of fan percentage (of maximal rotational speed).

With the bypass open (heat recovery switched off), the average undesired thermal efficiency is still 24%. Optimally, this efficiency would be 0%, but the fans add a small amount of heat (approximately 2°C) to the outdoor air, in spite of the use of efficient EC fans. If AC fans had been used, the thermal efficiency would be even higher.

With the bypass closed (heat recovery switched on), the optimal efficiency is obtained for the most frequently used fan position 1 (160 m^3/h). For the position ‘absent’ efficiency is decreasing, probably coming from imbalance in mass flows for very low flow regions. For higher fan speeds, the thermal efficiency is slowly decreasing because air is moving fast in the heat exchanger so that the limited exchanger surface becomes noticeable.

The observed average thermal efficiency with bypass closed is as high as 91%. This is a high number considering the fact that the supply air flow and the extract air flow are not perfectly balanced. The resident of the house has commissioned the HRU with a lower extract air flow than supply air flow rate. Detailed flow rate measurements revealed a 6% imbalance in volume flows. Mathematically, one can correct for this imbalance to obtain 91%/(100%-6%) = 97%. This means that, if the HRU system was commissioned in balanced flow, a thermal efficiency of 97% would be obtained, which corresponds perfectly with the thermal efficiency as measured in laboratory.

CONCLUSION

The monitoring of a demand controlled heat recovery ventilation system with ground heat exchange in a zero-energy building in Groenlo, The Netherlands, revealed interesting practical insights. A healthy indoor climate can be obtained with a high comfort in terms of CO_2 levels and supply air temperatures. The energy efficient behaviour is proven by the avoided heating load of 3465 kWh and free cooling of 1052 kWh during a full year. The observed seasonal performance factor SPF is 17 for the avoided heating and 8 for the free cooling.

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