Useful energy transfer in air-to-air heat recovery units in partly heated low energy buildings

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Abstract

In this study, the performance of ventilation systems with heat recovery in residential buildings with a low energy demand for heating was evaluated. In a completely heated building, the percentage of useful recovered heat will be equal to the nominal effectiveness of the heat exchanger. In the case some rooms are not heated, they will still receive preheated air. This part of the recovered heat will not directly increase comfort, so it does not completely contribute to the energy savings of the building. Simulations were done with TRNSYS to assess the percentage of usefully recovered heat. This value was found to be lower than the nominal effectiveness, but varying with several parameters.

Introduction

Balanced mechanical ventilation with air-to-air heat recovery units are used since the first energy crisis, particularly taking up significant market share in the last decade, to improve the energy efficiency of buildings.

A balanced ventilation system is usually equipped with two duct systems and two electrical fans, displacing the same amount of air. Polluted indoor air is extracted from the wet rooms (i.e. kitchen, bathroom and hall) and fresh outdoor air is supplied to the dry rooms (i.e. bedrooms, living room and study). When an air-to-air heat exchanger (AAHX) is installed between the two air streams, the cold supply air is preheated by the warm extracted air. The use of a heat recovery ventilation (HRV) system thereby reduces the heat demand of the building.

It was found in the studies by Binamu and Lindberg (2001), Roulet (2001) and Dodoo (2011) that the efficiency of the heat recovery drops when the building has a bad airtightness, because no energy can be recovered from air leakages. Figure 1, from the study of Roulet (2001), illustrates this effect by comparing the recovered ventilation energy, the energy loss through exhaust air and the energy loss through leakage air for a fully airtight building with that of a leaky building.

Different results were obtained by Juodis (2006), who studied the influence of the building's thermal properties on the efficiency of the heat recovery. The author defined a balance temperature of a building at which the internal heat gains compensate the losses. The closer the external temperature is to this balance temperature, the smaller the efficiency of the heat recovery, because the losses are already compensated by the gains. According to the author, the efficiency of the heat recovery decreases when a building has more insulation and better airtightness since this reduces the balance temperature of the building.

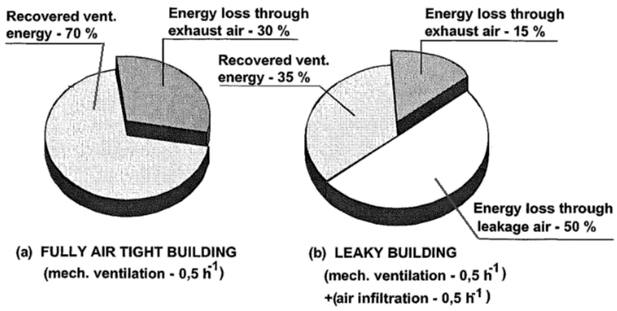

Figure 1: Comparison of heat recovery, ventilation and leakage losses for a fully airtight and a leaky building, Roulet (2001)

However, there is more. In a building where all rooms have a heat demand, the percentage of the heat in the extracted air that is usefully recovered is equal to the effectiveness of the AAHX. This effectiveness is used for the comparison of the performance of HRV systems. However, the occupants of a house do not always heat the entire building, but e.g. heat only the occupied rooms. The non-occupied dry rooms will in this case still receive preheated supply air. The heat in this air is recovered by the AAHX, but will not completely contribute to the reduction of the heat demand of the building. It will instead unnecessarily elevate the temperature in the empty rooms and increase the transmission and exfiltration losses to the exterior.

The present study investigated a method for the evaluation of HRV systems used in residential buildings with real occupancy profiles by the definition of a use factor, indicating what percentage of heat in the extracted air was usefully recovered. In addition to the assessment of the use factor, the influence of several parameters on this factor were determined. The parameters under investigation were the thermal properties of the building envelope and its occupancy, the ventilation flow rate, the nominal effectiveness of the heat exchanger and the desired comfort level.

In this paper, the method used to determine the use factor is explained first. This is followed by a discussion of the results for the different parameters. Finally, a conclusion is given.

Method

Model description

To investigate the performance of HRV systems, TRNSYS was used to simulate the building and calculate all room temperatures and heat demands. The study was limited to the Belgian climate, and only the heating period was taken into account.

The building investigated in this study was a two-storey detached building. In the house, there were a living room, a kitchen, a storage room, a study, three bedrooms and a bathroom. Three versions of this building, each equipped with a HRV system were created, differing in thickness of insulation and level of airtightness, resulting in an energy demand for heating, under a certain set of conditions, of *60 kWh/m²a*, *30 kWh/m²a* and *15 kWh/m²a*. These values are respectively the Belgian values for standard buildings, low-energy buildings and passive houses. To achieve these heat demands, first the airtightness was changed. An airtightness of *6 ach* (air changes per hour when a pressure difference of *50 Pa* between inside and outside is applied), *3 ach* and *0.6 ach* were used for the houses with a nominal energy demand for heating of *60 kWh/m²a*, *30 kWh/m²a* and *15 kWh/m²a*, respectively. Afterwards, the thickness of insulation in the external walls and the roof was iteratively adjusted until the energy demand for heating reached the desired value. The average U-values of the external walls for the three versions of the building were *0.404 W/m²K*, *0.243 W/m²K* and *0.205 Wm²K* respectively.

For the ventilation system, the extracted and supplied flow rates were calculated according to the Belgian standard NBN D 50-001 (BIN, 1991). This standard demands a ventilation flow rate of *3.6 m³/h* per m² floor area for each room. To investigate the influence of the ventilation flow rates on the performance of the HRV system, simulations were also done where the flow rates were scaled with a factor *2/3* and *1/3*, representing typical use cases, since most systems in Belgium have a 3-position control switch. In addition to these continuous flow cases, a demand controlled ventilation condition (DCV) was also considered.

This DCV-strategy was based on the maximum CO_2-concentration in the building and was implemented as a simple on/off-strategy. The ventilation was turned on when the maximum CO_2 level in the building exceeded *1000 ppm* and was reduced to 10% of the nominal flow rate (*off-state*) when this concentration dropped below *900 ppm*. The atmospheric concentration of CO_2 was chosen to be 400 ppm and the generation by people was modelled as $1.2 \cdot 10^{-5}$ *kg/s* and $6.7 \cdot 10^{-6}$ *kg/s* per person that is awake or asleep respectively (based on ASHRAE, 2009).

The AAHX in the ventilation system was modelled as a plate heat exchanger with an effectiveness of 75%, 80% or 85% at nominal flow rates. When the ventilation flow rates decrease, the effectiveness of the heat exchanger increases. As was also done by Chel (2015), this relation between flow rate and effectiveness was modelled with the ε-NTU correlations for a crossflow heat exchanger, given by Kakac (2012). This correlation, where the assumption of equal supply and extraction flow rates was made, is given by equation (1) and illustrated by figure 2.

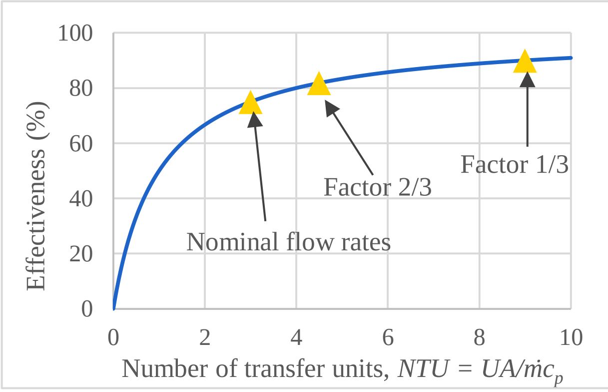

Figure 2: The ε-NTU correlations for a crossflow heat exchanger, Kakac (2012)

$$\varepsilon = \frac{NTU}{1+NTU} \qquad (1)$$

The number of transfer units, NTU, is a dimensionless group, defined as $UA/\dot{m}c_p$, with the average heat transfer coefficient U (W/m^2K), surface area A (m^2), the mass flow rate $\dot{m}$ (kg/s) and the specific heat capacity c_p (J/kgK).

Also indicated on figure 2 are effectivenesses for the nominal flow rates and the flow rates reduced with a factor 2/3 and 1/3. Since the number of transfer units is inversely proportional to the flow rates, the effectiveness increases with decreasing flow rates to 81.8% and 90% respectively, for a nominal effectiveness of 75%.

For this study, a heating strategy was chosen where not all rooms are heated simultaneously. A room was instantly heated (unlimited heating power) to the desired temperature, only when someone is present in this room. The set-point temperatures to which each occupied room was heated, were depending on the desired comfort. Three comfort levels were defined (denoted by *low*, *medium* and *high*), each with set-point temperatures calculated from Peeters (2009). In this study, the author determined comfortable indoor temperatures based on the current and recent outdoor temperatures, this way taking thermal adaption into account. These comfortable temperatures were used as desired set-point temperatures for the *medium* comfort level. The lower and upper boundaries of the *10 PPD* range (Predicted Percentage of Dissatisfied) around these comfortable temperatures were respectively used for the set-point temperatures of *low* and *high* comfort level.

Besides three comfort levels, two realistic occupancy profiles were modelled. A mostly absent and a mostly at home profile were considered, for a household with two people. These profiles were based on Aerts (2014), who studied a Belgian time-use survey containing activity data from 6400 individuals and 3474 households.

Figure 3 shows for each occupancy profile the cumulative probability of someone being at home and awake (H), sleeping (S) or absent (A) for 24 hours.

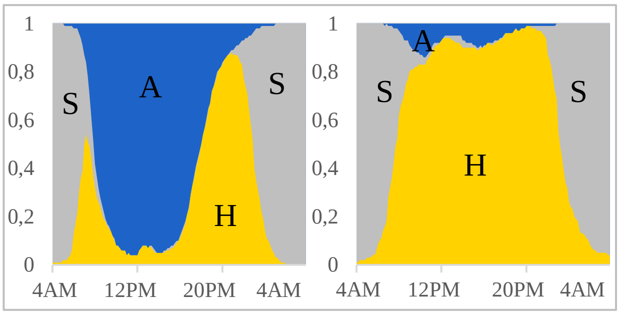

Figure 3: Cumulative probability for someone being home and awake (H), sleeping (S) or absent (A) for the mostly absent (left) and mostly at home (right) occupancy profiles, Aerts (2014)

Performance indicators

To evaluate the performance of the HRV system in a building where not every room is heated, a use factor was defined, indicating the percentage of the extracted heat that is recovered by the AAHX and supplied usefully to the building.

To calculate this factor, three heat demands of the buildings were used, each determined with a different simulation.

The first heat demand, Q, is the resulting heat demand for a building with a given set of parameters.

A second simulation was performed where the heat demand was calculated for the same building with the same set of parameters. The only difference was that here, the effectiveness of the heat exchanger was reduced to 0% (or no heat exchanger was installed between the two air flows). This value was called Q_0, and will always be higher than the value of Q, because none of the heat in the extracted air is recovered and the supply air will be at outdoor air temperatures.

The third and last heat demand was determined for again the same building, but where no ventilation was present (both supply and extraction flow rates were reduced to *0 m³/h*). The resulting heat demand was denoted Q_{NV} and represents the transmission and infiltration losses. Since no warm air is extracted and no cold air is supplied, this will always be lower than the value of Q.

When these values were determined from the simulations, the use factor could be calculated. The value of $Q_0 - Q$ gives an indication of the amount of heat that was usefully recovered by the heat exchanger. This value should be divided by the maximum amount of heat the AAHX could recover. Since the heat demand without ventilation is the optimum for a building with a certain set of parameters, this maximum is indicated by $Q_0 - Q_{NV}$. The resulting use factor η *is*:

$$\eta = \frac{Q_0 - Q}{Q_0 - Q_{NV}} \qquad (2)$$

Results and discussion

In the current study, the influence of each parameter on the performance of the HRV system was studied by first investigating a base case and then comparing the results to the case where each time only one of the parameters was changed.

This base case was defined as the detached building with a nominal energy demand for heating of *60 kWh/m²a*. The ventilation was always on, with the nominal flow rates. The heat exchanger had an effectiveness of 75% and the occupants, which are mostly absent, desired a medium comfort level.

Base case

The results for the building of the base case are illustrated by figure 4. The actual heat demand, Q, was equal to *30.67 kWh/m²*. This was lower than the nominal heat demand of *60 kWh/m²a*, due to the use of a realistic occupancy profile (mostly absent) in contrast to the continuous heating used for the determination of the nominal heat demand. The values of the fictitious heat demands without heat exchanger and without ventilation, Q_0 and Q_{NV}, were *48.41 kWh/m²* and *16.83 kWh/m²* respectively.

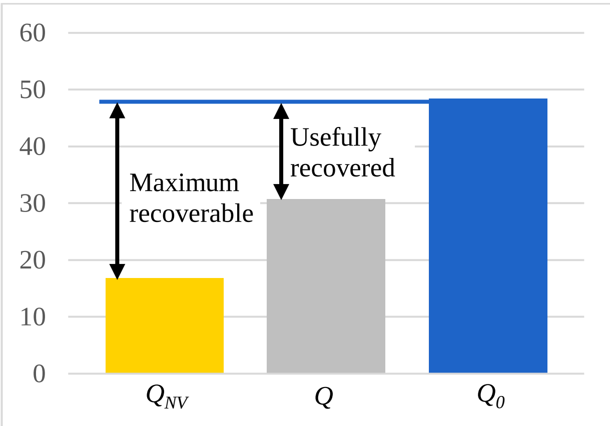

Figure 4: The heat demand without ventilation, the actual heat demand and the heat demand without heat recovery for the base case

The heat that was usefully recovered and supplied to the building was *17.74 kWh/m²*, while the maximum recoverable amount was *31.58 kWh/m²*. With these values, a use factor η, of 56.2% was obtained. This shows that, although the AAHX had a nominal effectiveness of 75%, only 56.2% of the heat in the extracted air was recovered by the heat exchanger and subsequently supplied to the building usefully. Some of the recovered heat did reach the heated rooms with the internal air flows, but a significant fraction, in this case 25.1% of the recovered heat, was lost to the exterior because of transmission and exfiltration losses. This means that preheated air was supplied to rooms that were not occupied and elevated their temperature or was lost due to sufficient internal gains in accordance with Juodis (2006). In his study, the author reported a difference of 10% to 20% between the nominal effectiveness and the mean annual effectiveness, depending on the climate, the building and the nominal effectiveness, which is comparable to the obtained difference of 18,8% in this study.

Influence of parameters

Building insulation and airtightness

The base case had a nominal energy demand for heating of *60 kWh/m²a*. By increasing the level of insulation and airtightness, nominal heat demands of *30 kWh/m²a* and *15 kWh/m²a* were reached. The resulting use factors are shown in figure 5.

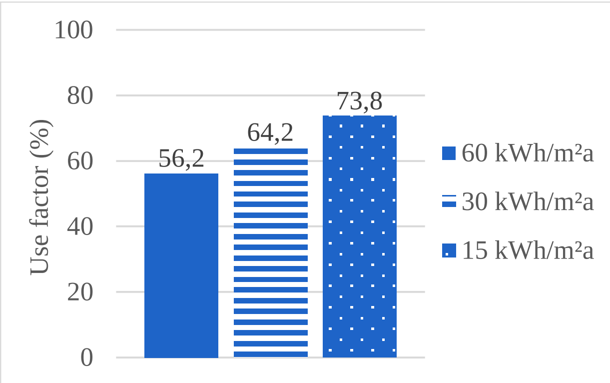

Figure 5: Influence of level of insulation and airtightness on the heat recovery use factor

Improving the energy efficiency of the building, and thereby reducing the nominal heat demand, had a beneficial effect on the use factor. For the building with the most insulation and the best airtightness, a use factor of 73.8% was reached, approaching the nominal effectiveness of the heat exchanger.

These higher use factors indicate that a higher percentage of the heat in the extracted air could contribute to reducing the heat demand of the building. This was caused by the fact that the elevated temperatures in the non-heated rooms did to less extend lead to higher transmission and exfiltration losses. Due to the higher thermal insulation, the indoor temperature is higher and more uniform throughout the dwelling (Delghust, 2015), also increasing the exhaust temperature.

These results contradict Juodis (2016), but are in line with the findings of Binamu and Lindberg (2001), Roulet (2001) and Dodoo (2011), who also concluded that improving the airtightness and increasing the thickness of the insulation increases the efficiency of the heat recovery.

An illustration of the fact that the supplied heat is more equally distributed in the building, is the higher temperature in the hall (non-heat zone), which acts as a passageway for air flowing from the rooms with supply of fresh air to the rooms with extraction of indoor air. This is illustrated by figure 6, displaying the average hall temperature in January for the three buildings.

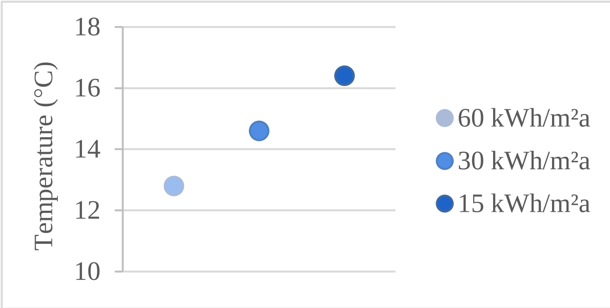

Figure 6: Average temperature in the hall in January for the three levels of insulation and airtightness

Occupancy

As mentioned before, two different occupancy profiles were defined. The first occupancy profile, used in the base case, modelled a household which was mostly absent. The people from the second occupancy profile were mostly at home.

In figure 7, the resulting use factors for the two occupancy profiles are given. A higher percentage of the extracted energy was usefully recovered with the higher occupancy. Since more rooms were heated more often, less preheated air was supplied to rooms that did not require this energy. Hence, there were less unnecessary transmission and exfiltration losses and the useful fraction increased.

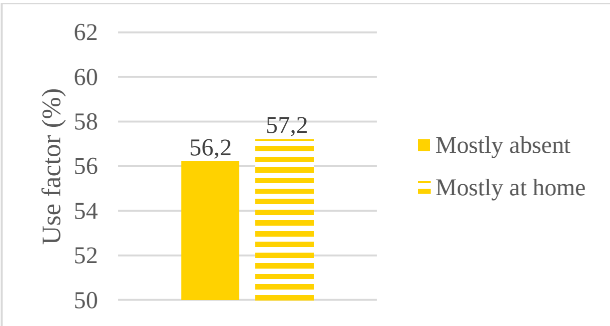

Figure 7: Influence of the occupancy profile on the heat recovery use factor

Although, with the second occupancy profile, most of the time one or more rooms were heated, only a small fraction of the building was heated at one instant, leading to a still rather low occupancy. Therefore the use factor was calculated for cases where some rooms were heated regardless of the presence of someone in that room, for investigating higher occupancies.

The results for these higher occupancies are given in figure 8. The occupancy is expressed as a percentage based on both time heated and heated floor area. If every room was heated 24/7 the occupancy would be 100%. The occupancies for the two original profiles were 12.4% and 19.2%.

The same trend as with figure 7 can be observed. Higher occupancy means less preheated air to non-heated rooms, resulting in a higher use factor.

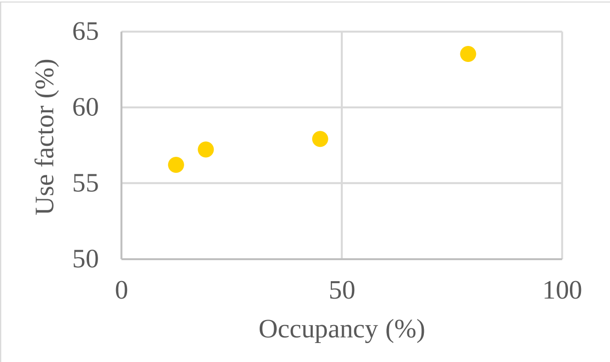

Figure 8: Use factors for more occupied buildings

Nominal heat exchanger effectiveness

The building in the base case was equipped with a heat exchanger with a nominal effectiveness of 75% and the resulting use factor was 56.2%. This means that, for this case, 74.9% from the heat that was recovered by the heat exchanger was supplied usefully.

The resulting use factors for the same building, but with a nominal heat exchanger effectiveness of 80% and 85% were 59.9% and 63.6% respectively.

Similar to the base case, the fractions of the recovered heat that contributed to a lower heat demand were here 74,9% and 74,8% respectively. This means that the use factor scales linearly with the effectiveness of the heat exchanger. These results also imply that the installation of a heat exchanger with an effectiveness of 100% could not usefully recover all heat in the extracted air. It was confirmed with simulations that the use factor in the fictitious case with a perfect heat exchanger installed in this building would be approximately 75%.

The results for the different nominal heat exchanger effectivenesses are shown in figure 9. A linear relationship can clearly be observed.

Ventilation flow rates

To investigate the influence of the ventilation flow rates on the performance of a HRV system, the use factors were determined for the building with the flow rates reduced with a factor 2/3 and 1/3. As is shown above, the effectiveness of the heat exchanger increased in these cases to 81.8% and 90% respectively.

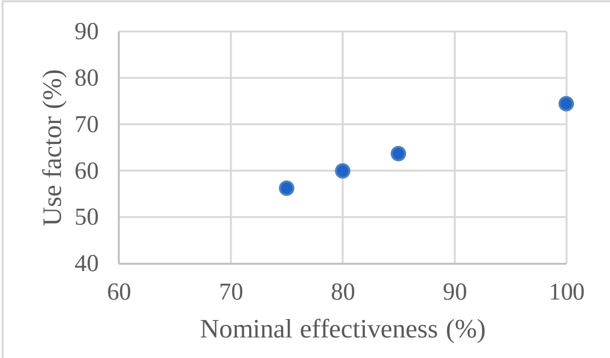

Figure 9: Influence of the nominal effectiveness of the AAHX on the use factor

Based on the discussion of the influence of the heat exchanger effectiveness on the use factor, where it was shown that the use factor scales linearly with the effectiveness, expected use factors can be calculated by multiplying the effectiveness with 74,9%. The expected values and the real use factors determined with simulations are shown in figure 10.

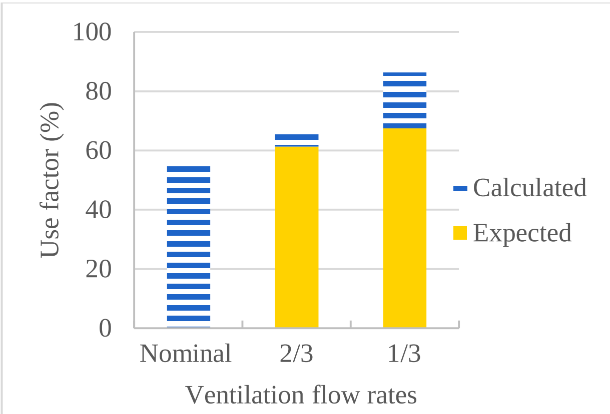

Figure 10: Expected and calculated use factors for the nominal ventilation flow rates and the flow rates reduced with a factor 2/3 and 1/3

It was observed that the resulting use factors are higher than the expected ones, calculated from the heat exchanger effectiveness. So lowering the flow rates did not only increase the effectiveness of the heat exchanger, but also increased the fraction of the recovered heat that contributes to the decrease of the heat demand.

Important to note when comparing the cases with different flow rates is that by decreasing the flow rates, the indoor air quality deteriorates. The average CO_2-concentration in the occupied rooms increased from *667 ppm* for the highest flow rates to *1025 ppm* for the lowest flow rates.

Desired comfort

Three comfort levels were earlier defined, each with different set-point temperatures. While the use factor for the base case (*medium* comfort level) was 56.2%, the

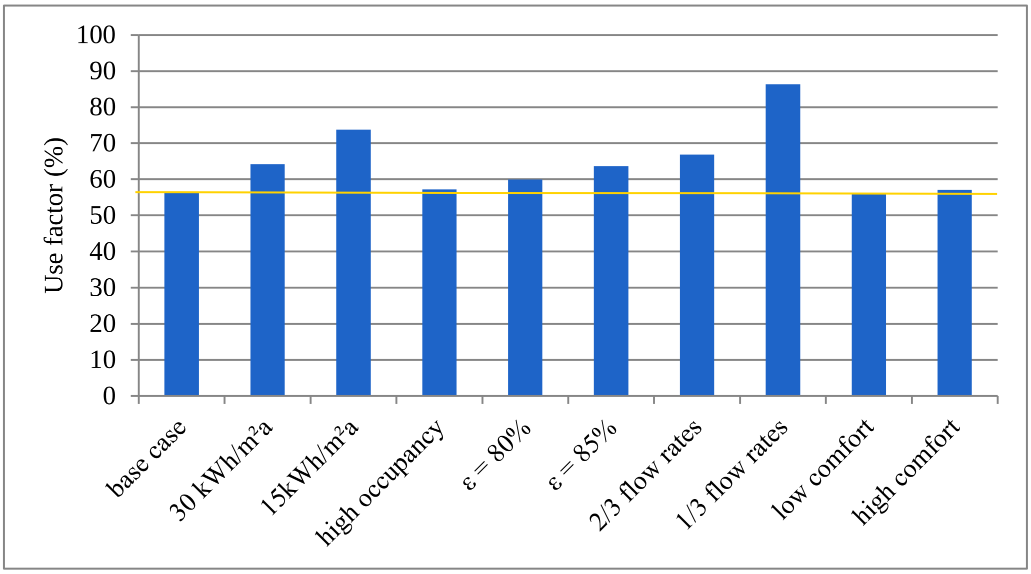

Figure 11: Overview of the use factor for the different cases. The horizontal line indicates the use factor of the base case.

resulting use factors for the *low* and *high* comfort level were 56.0% and 57.1% respectively. The small decrease of use factor with decreasing comfort level was caused by the fact that when the comfort level is low and the set-point temperatures decrease, the heated rooms will sooner reach their desired temperature. At that moment, recovered energy in the preheated air that is then supplied no longer completely contributes to reducing the heat demand.

An overview of the use factors for the discussed case is given in figure 11. It can be seen that the parameters with the biggest influence are the ventilation flow rates and the thermal properties of the building.

Conclusion

In this study, a method for the assessment of the performance of HRV systems in real conditions was investigated. A use factor was defined, indicating what percentage of the extracted heat was usefully recovered. Its calculation was based on three different heat demands. The first heat demand was the actual heat demand of a building under certain conditions. The other two heat demands were fictitious, determined for the same building, but once without an AAHX between the two air ducts and once without any ventilation in the building.

It was seen that this use factor is lower than the nominal effectiveness of the heat exchanger. In the investigated case, a value of 56% was found, while the effectiveness was 75%. By improving the airtightness and increasing the insulation thickness, the fraction of usefully recovered energy could be increased, approaching this effectiveness. A higher occupancy of the building also led to higher use factors. The use factor increased linearly with increasing nominal heat exchanger effectiveness. Decreasing the flow rates increased the use factor as well. This elevated the heat exchanger effectiveness and increased the fraction of the recovered heat that was usefully supplied. The influence of the desired comfort level on the use factor was small, but demanding a higher comfort level increased the use factor.

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