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Retrofit of Multi-Family Homes with Central Heat Recovery Ventilation, Learnings from Three Case Studies

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Abstract

This paper addresses the implementation of ventilation systems within the context of energy retrofit of residential buildings. Indoor air quality is a parameter of crucial importance when the airtightness of the building envelope is increased. A mechanical ventilation system is required and may strongly influence the energy demand of the building and the user comfort. Three German multifamily homes have undergone deep energy retrofits and have been equipped with central ventilation systems with heat recovery. An analysis of their implementation and of the results provided by a long-time monitoring is proposed. A definition of the heat recovery efficiency taking the electricity demand and primary energy coefficients into account is proposed and implemented to evaluate the performance of the three analysed ventilation systems. It can be concluded that the implementation of central heat recovery ventilation systems in the energy retrofit of residential buildings provides a high thermal comfort as well as good energy performances despite the differences between these performances and the ones expected during the planning phase and despite the difficulties to operate these systems correctly.

Keywords - Ventilation; Heat recovery; Energy efficiency; Building retrofit

1. Introduction

Ventilation represents a major challenge within the context of energy retrofit of residential buildings. The percentage of the European housing stock equipped with mechanical exhaust ventilation reaches only 36 % and with heat recovery ventilation only 1 % [1]. Different examples show that heat recovery ventilation can be implemented within the retrofit of multi-family homes [14]. At first, the definition of the heat recovery efficiency will be discussed. In the next part, three case studies will be presented and the performances of their ventilation systems will be analysed, considering their energy performance but also other criteria like thermal comfort and inside air quality. At last, a comparison with a ventilation system without heat recovery will be proposed and the influence of parameters like the imbalance between supply and exhaust airflows of the user behaviour will be analysed.

2. Definition of heat recovery efficiency

Nomenclature, illustrated by figure 1:

- c_p specific heat capacity
- \dot{m}_{\max} highest value between supply and exhaust mass airflows
- $\dot{m}_{\text{infiltrations}}$ Mass airflow of the infiltrations due to the ventilation system
- P_{elec} Electrical power of the fans
- P_{heating} Heat demand covered by the heating system
- $P_{\text{heating-v}}$ Heat demand covered by the heating system due to ventilation
- $\dot{Q}_{\text{infiltrations}}$ Heat transferred by the infiltrations
- $\dot{Q}_{\text{in-nh}}$ Heat transferred between heated and non-heated spaces
- $\dot{Q}_{\text{in-nh}}^{\circ}$ Theoretical heat transferred between heated and non-heated spaces in absence of ventilation
- $T_{\text{exh-0}}$ Exhaust air temperature at the outlet of the air duct
- $T_{\text{exh-1}}$ Exhaust air temperature at the outlet of the ventilation device
- $T_{\text{in-0}}$ Inside air temperature in the dwelling at the inlet of the air duct
- $T_{\text{in-1}}$ Inside air temperature at the inlet of the ventilation device
- $T_{\text{out-0}}$ Outside air temperature at the inlet of the air duct
- $T_{\text{out-1}}$ Outside air temperature at the inlet of the ventilation device
- $T_{\text{sup-0}}$ Supply air temperature in the air duct at the interface between heated and non-heated spaces
- $T_{\text{sup-1}}$ Supply air temperature at the outlet of the ventilation device

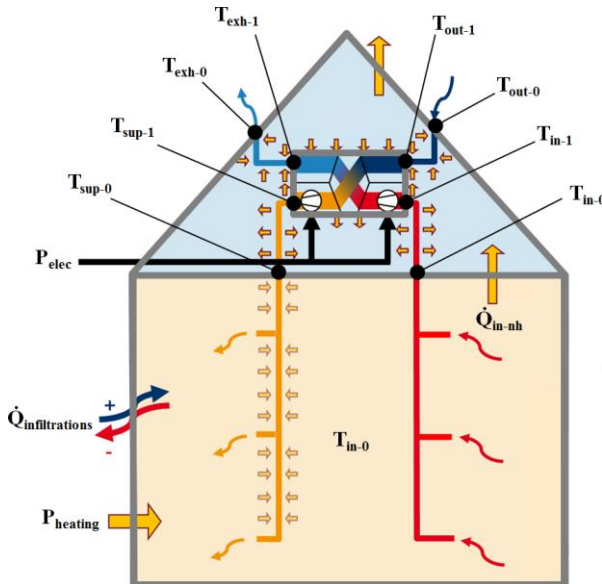


Fig. 1 Building with heat recovery ventilation (example: device in a non-heated attic)

Different standards and certification methods propose definitions of the heat recovery efficiency. The following ones are compared in this paper: EN308 [2], EN13053 [3] and the Passivhaus test procedure [4].

$$\eta_{\text{EN308}} = \frac{T_{\text{sup-1}} - T_{\text{out-1}}}{T_{\text{in-1}} - T_{\text{out-1}}} \quad (1)$$

$$\eta_{\text{EN13053}} = \frac{T_{\text{sup-1}} - T_{\text{out-1}}}{T_{\text{in-1}} - T_{\text{out-1}}} \cdot \left(1 - \frac{P_{\text{elec}}}{\dot{m} \cdot c_p \cdot (T_{\text{in-1}} - T_{\text{out-1}})} \right) \quad (2)$$

$$\eta_{\text{PHI}} = \frac{T_{\text{in-1}} - T_{\text{exh-1}} + \frac{P_{\text{elec}}}{\dot{m} \cdot c_p}}{T_{\text{in-1}} - T_{\text{out-1}}} \quad (3)$$

A frequent criticism against these conventional methods is that they do not represent the real energy savings reached in operational conditions and that they provide overestimated values of the heat recovery efficiency. Therefore a definition is proposed, basing the calculation on the energy demand due to the ventilation system compared to a reference case, consisting in a theoretical ventilation system providing the same airflow as the evaluated system, without heat recovery and without electricity consumption. The reference heat demand can be determined as following:

$$P_{\text{ref-v}} = \dot{m}_{\text{max}} \cdot c_p \cdot (T_{\text{in}} - T_{\text{out}}) \quad (4)$$

The difference between supply and exhaust airflows is considered as infiltrations due to the ventilation system with the following mass air flow:

$$\dot{m}_{\text{infiltrations}} = \dot{m}_{\text{exh}} - \dot{m}_{\text{sup}} \quad (5)$$

and the corresponding heat flow is:

$$\dot{Q}_{\text{infiltrations}} = \dot{m}_{\text{infiltrations}} \cdot c_p \cdot T_{\text{out-0}} \quad (6)$$

The determination of the heat demand covered by the heating system and due to ventilation is based on a heat balance of the building [5]. It results from the difference between the measured heat demand and the theoretical heat demand in absence of ventilation. For example, if the ventilation device is placed in a non-heated room, this heat demand can be determined by:

$$P_{\text{heating-v}} = \dot{Q}_{\text{nh-out}} - \dot{Q}'_{\text{nh-out}} + \dot{m}_{\text{exh}} \cdot c_p \cdot T_{\text{exh-0}} - \dot{m}_{\text{sup}} \cdot c_p \cdot T_{\text{out-0}} - \dot{Q}_{\text{infiltrations}} - P_{\text{elec}} \quad (7)$$

The instant heat recovery efficiency is the ratio of the heat demand reduction on the reference heat demand:

$$\eta_{\text{i-HRC}} = \frac{P_{\text{ref-v}} - P_{\text{heating-v}}}{P_{\text{ref-v}}} \quad (8)$$

This heat recovery efficiency only characterises the reduction of the heat demand due to the heat recovery. In order to characterise the global energy

performance of the ventilation system, an instant energy efficiency, taking the electrical consumption of the fans into account, is defined in (9) for a final energy approach and in (10) for a primary energy approach:

$$\eta_{i-fe} = \frac{P_{ref-v} - P_{heating-v} - P_{elec}}{P_{ref-v}} \quad (9)$$

$$\eta_{i-pe} = \frac{f_{pe-heat} \cdot P_{ref-v} - f_{pe-heat} \cdot P_{heating-v} - f_{pe-elec} \cdot P_{elec}}{f_{pe-heat} \cdot P_{ref-v}} \quad (10)$$

The seasonal performance can be evaluated by integrating each heat flow over one year and can be expressed in final or primary energy:

$$\eta_{s-fe} = \frac{Q_{ref-v} - Q_{heating-v} - Q_{elec}}{Q_{ref-v}} \quad (11)$$

$$\eta_{s-pe} = \frac{f_{pe-heat} \cdot Q_{ref-v} - f_{pe-heat} \cdot Q_{heating-v} - f_{pe-elec} \cdot Q_{elec}}{f_{pe-heat} \cdot Q_{ref-v}} \quad (12)$$

3. Case studies

The 3 case studies presented here are described in Table 1. For the first one (*Rislerstraße* in Freiburg), a neighbour building has been simultaneously retrofitted with a slightly less performant energy concept including a ventilation system without heat recovery [6, 7]. As both buildings are very similar, this enables a good comparison between their systems. The second building is situated in Heidelberg [6, 8] and has been equipped with a combined heat and power (CHP with 50 kW_{el} and 80 kW_{th}) and two peak load boilers (each 92 kW), all based on natural gas. This has of course an important impact on the primary energy evaluation of the ventilation system.




The last building is a high-rise building (with 16 storeys) and has the specificity that its retrofit aimed to reach the Passivhaus Standard. An additional storey was built for the new ventilation system so that it is the only case where the ventilation device is placed in a non-heated room. The building is connected to a district heating, also with CHP which lead to an extremely low primary energy factor [9].

The heat recovery indicated in Table 1 is the value declared by the manufacturer ($\eta_{manufacturer}$).

4. Results

The first outcome of Fig. 2 is the high spread between all evaluation methods. The second outcome is that the conventional methods indeed overestimate the heat recovery efficiency and that the heat recovery efficiency in operational environment is considerably lower as the one declared by the manufacturer.

Table 1. Description of the 3 case studies

	Rislerstraße 1-5 (Freiburg)	Blaue Heimat (Heidelberg)	Bugginger Straße 50 (Freiburg)
Year of retrofit	2005	2005	2010
Type of retrofit	Insulation, windows, new balconies, new heating system, new ventilation system, KfW 40 standard	Insulation, windows, new balconies, new heating system with CHP, new ventilation system, KfW 40 standard	Insulation, windows, new balconies, district heating with CHP, new ventilation system, Passivhaus standard
Number of dwellings	18	40	before retrofit: 90 after retrofit: 144
Net heated floor area	1232 m ²	3374 m ²	before retrofit: 7200 m ² after retrofit: 8582 m ²
Type of ventilation system	Central balanced ventilation with heat recovery (90%) 3 devices placed in heated rooms, each device for 6 dwellings	Central balanced ventilation with heat recovery (85%) 9 devices placed in heated rooms, each for 4 or 6 dwellings	Central balanced ventilation with heat recovery (77%) 2 devices placed in non-heated attic: AHU 1: 3700 m ³ /h AHU 2: 4200 m ³ /h
Primary energy factor	$f_{pe-heat} = 1.1$ [10]	$f_{pe-heat}$ [10]	$f_{pe-heat} = 0.24$ [11]
Monitoring	One device was monitored	Two devices were monitored (AHU1 and AHU9)	Both devices monitored user behaviour (inside temperature and window openings) monitored in 27 dwellings
Monitoring period	26.11.2008 to 31.12.2009	19.08.2008 to 31.12.2009 (part of the data only available from 19.07.2009 to 31.12.2009)	01.01.2012 to 31.12.2013
Picture after retrofit			

In comparison with the heat recovery efficiency defined in (8), the final energy efficiency (11) is decreased by the consideration of the electrical consumption of the fans. The primary energy calculation (12) increases the impact of the electrical consumption. For the *Blaue Heimat*, Fig. 3 shows that values below 0 are appearing as soon as the outside temperature reaches 13 °C. The seasonal primary energy efficiencies of both devices remain above 0 indicating that heat recovery is globally saving more primary energy as it consumes.

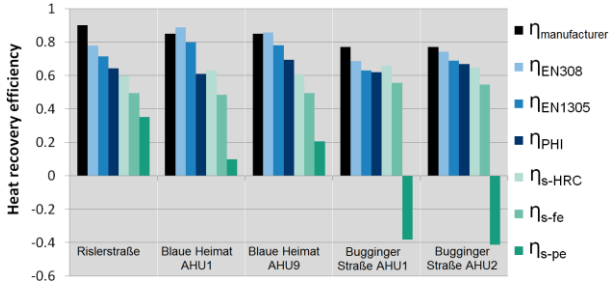


Fig. 2 Heat recovery efficiency

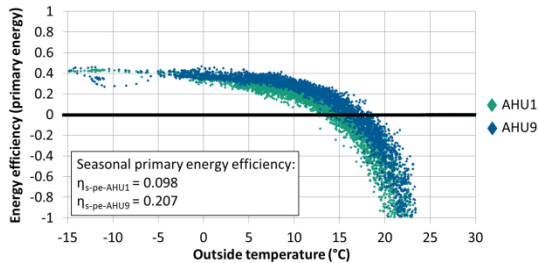


Fig. 3 Blaue Heimat: Primary energy efficiency according to (10) as a function of the outside temperature (hourly data - 2009)

For the *Bugginger Straße*, the extremely low primary energy factor for heat leads to negative seasonal primary energy efficiencies for both devices, even if the measured Specific Fan Power (SFP) of each ventilation device (0.362 Wh/m^3 for AHU 1 and 0.368 Wh/m^3 for AHU 2) is much lower as the Passivhaus requirement of 0.45 Wh/m^3 . These negative values mean that the primary energy consumption of the ventilation system is superior to the benefit provided by the heat recovery. As explained by Winniger [12], with rising generation from renewable energies the primary energy factor of electricity in Germany is going to be decreased, leading to higher primary energy factors of cogeneration systems. Both of these evolutions will lead to an increase of the primary energy efficiency of ventilation with heat recovery. Therefore, heat recovery will remain an interesting technology in the future.

5. *Rislerstraße*: comparison with exhaust ventilation

Fig. 4 shows the final and primary energy consumptions of the ventilation systems in the *Rislerstraße* 1-5 (heat recovery ventilation) and *Rislerstraße* 7-13 (exhaust ventilation).

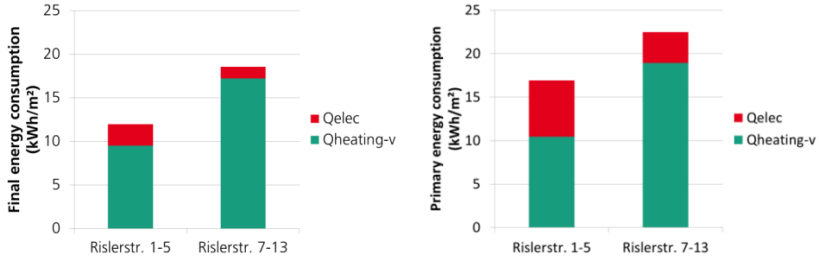


Fig. 4 *Rislerstraße* 1-5 and 7-13: final (left) and primary (right) energy consumptions of the ventilation systems (2009)

The electrical power of the fans in Haus 1-5 corresponds to an average SFP of 0.406 Wh/m^3 and in Haus 7-13 to an average of 0.249 Wh/m^3 . The final energy consumption for Haus 1-5 is reduced by 35 % in comparison with Haus 7-13 and the primary energy consumption only by 25 %. The air quality provided by both ventilation systems can be investigated by the CO_2 concentrations in the exhaust air (Fig. 5). As the CO_2 sensors had a defect, the measurements are only available for a few days at the end of the year 2009. Even if the spread of both measurements is rather large, it can be observed that the CO_2 concentration decreases when the outside temperature increases. This can be explained by two reasons:

- the window opening frequency increases with the outside temperature, adding a natural ventilation to the forced ventilation that cannot be detected by our measurements,
- the tenants are more going outside, reducing the occupation rate and therefore the CO_2 emissions at higher outside temperatures.

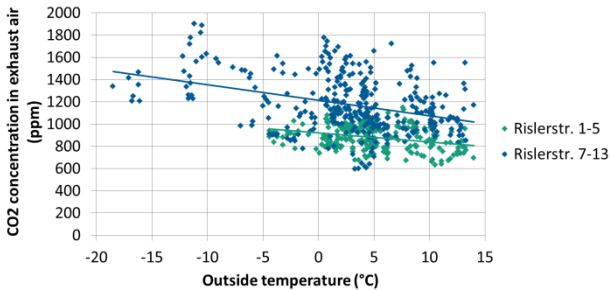


Fig. 5 *Rislerstraße*: CO_2 concentrations in exhaust air as a function of the outside temperature (hourly data - Haus 1-5: 21.12.2009 to 31.12.2009 - Haus 7-13: 18.12.209 to 31.12.2009)

A second observation is the higher average concentration for Haus 7-13 as for Haus 1-5 that can easily be explained by the different air change rates (0.24 vol/h for Haus 7-13 and 0.29 vol/h for Haus 1-5). One supposition to explain why these air change rates are different is the user behaviour. It is typical for exhaust ventilation systems by too cold supply air temperatures to see the tenants closing the air inlets or filling them with material in order to avoid feeling draughts caused by ventilation air. In this case the lower indoor air quality would be directly caused by the lack of heat recovery.

6. Impact of the difference between supply and exhaust airflows

The influence of the imbalance between supply and exhaust airflows is illustrated in Fig. 6. An imbalance of around 25 % leads to a reduction of the heat recovery efficiency of around 10%.

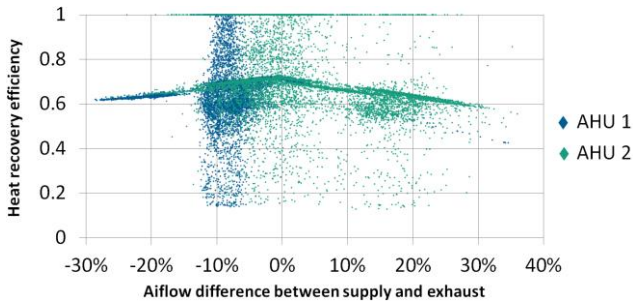


Fig. 6 Bugginger Straße 50: Heat recovery efficiency (8) as a function of the airflow difference between supply and exhaust (hourly data - 2013)

7. User behaviour

The user behaviour has been analysed (only for the Bugginger Straße) through two parameters: the percentage of opened windows (Fig. 7) and the indoor temperatures (Fig. 8).

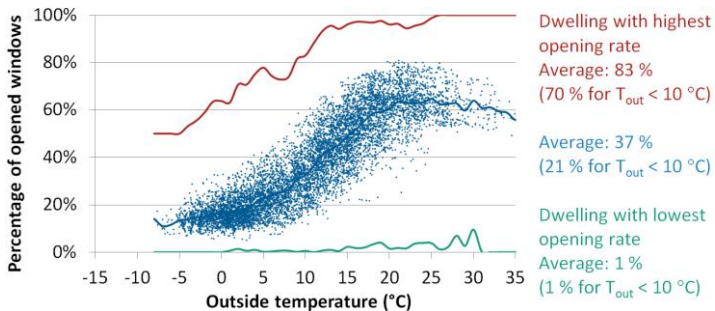


Fig. 7 Bugginger Straße 50: Percentage of opened windows as a function of the outside temperature (hourly data - 2013)

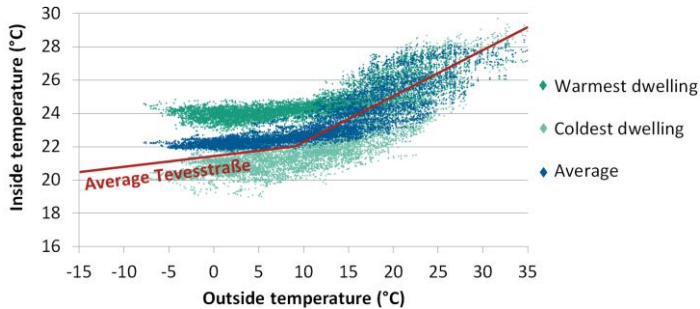


Fig. 8 Bugginger Straße 50: Indoor temperature as a function of the outside temperature (hourly data - 2013)

The average percentage of opened windows is quite similar to the observations made by Herkel [13] but the difference between the dwelling with the highest opening rate and the dwelling with the lowest opening rate shows the high diversity of user behaviours. As the average percentage is quite similar to buildings without ventilation systems, the influence of a ventilation system on the natural ventilation due to window openings can be neglected.

For indoor temperatures, a wide spread can also be observed on Fig.8. The average temperature is slightly higher as the one measured in a similar project (retrofit of a multi-family home in the *Tevesstraße* - Frankfurt [14]). Through a correlation between indoor temperature, window opening rate and heat consumption of each dwelling, it could be concluded that both following actions increase the energy consumption of around 10 kWh/m².a:

- increase of the average indoor temperature of 1 K,
- increase of the average window opening rate of 30 %.

8. Conclusion

The main conclusion is that even if their real efficiency does not reach the values declared by the manufacturer or determined by conventional methods, ventilation systems with heat recovery are still leading to primary energy savings in most of the cases. Additionally to this advantage, thermal comfort and indoor air quality are increased in comparison to exhaust ventilation without heat recovery.

Efforts still have to be directed towards improving the operation of the systems, for example by adjusting the balance between supply and exhaust airflows. The users also have to change their behaviours and reduce their window opening rates in presence of a mechanical ventilation system.

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