DEEP RENOVATION OF MULTI-FAMILY-HOUSES WITH COMPACT HEAT PUMPS

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SUMMARY

Within the framework of the Austrian FFG project "SaLüH!" concepts with high energy efficient and cost-effective decentral small scale heat pumps for heating and domestic hot water preparation for the renovation of small dwellings in multi-story buildings are developed and investigated. Very compact heat pumps are developed in order to enable the integration of these units into the window parapet or into the façade. The wall integration has a high potential in pre-fabrication and leads to an optimal solution for renovation of small apartments. The target is to create a complete renovation package with a decentralized (apartment size) exhaust-air heat pump (HP) for ventilation and heating installed in the kitchen and an air-to-water HP for domestic hot water (DHW) preparation installed in the bathroom. The solutions aim to be cost effective, involving components and technologies with high efficiency and minimum noise emissions. In addition, further aspects such as handling, compactness, attractiveness, maintenance, etc. are of high relevance to enable a minimum disruptive renovation.
Keywords: Renovation, Multi-Family House, heat pump, façade integration, modelling and simulation

INTRODUCTION

Experience shows that for multi-family houses (MFH), a complete renovation including conversion to central heating and DHW systems is hardly possible. Installation work inside the inhibited flats are often associated with number of complications (technical, legal, financial). Thus the centralization of ventilation, heating and DHW is often dropped. Unfortunately, energy and cost efficient decentralized (and less invasive) solutions are also not available. Hence, new innovative concepts for heating, ventilation and DHW preparation are investigated. Very compact heat pumps are developed in such a way that it will be possible to integrate these units into the window parapet or into a prefabricated timber façade. The wall integration has a high potential in pre-fabrication and leads to an optimal solution for the renovation of small apartments. The target is to create a complete renovation package with a decentralized (apartment size) exhaust-air HP for ventilation and heating installed in the kitchen and a DHW-HP in the bathroom, see Fig. 1.

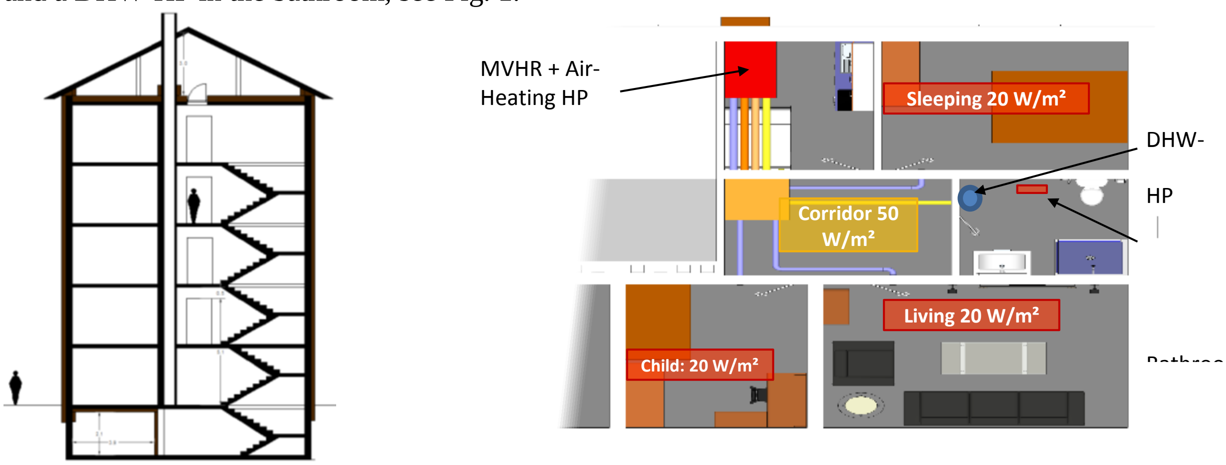

Fig. 1: (left) Typical MFH and (right) heat load (in W/m²) of the thermal zones with optional recirculation air heating in the corridor; Ventilation and HP in the kitchen and DHW HP in the corridor

SUPPLY AIR HEAT PUMP WITH SECONDARY AIR RECIRCULATION

Supply Air Heat Pump

A MVHR unit is, in many cases, one of the first steps for a deep energy renovation of a building in order to improve the IAQ, to reduce the ventilation losses and to maintain thermal comfort. The ducts, necessary for the ventilation system, can be used to distribute space heating power, using a supply air heat pump system. Fig. 2. shows the 3D view of the flat with the proposed system and a simplified scheme of the system Ochs et al. 2017.

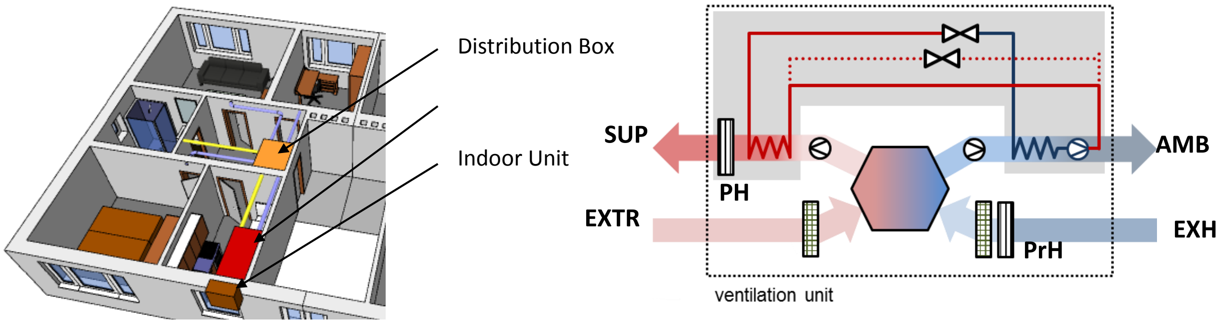

Fig. 2: 3D view of the flat with the supply air heat pump system (left) and scheme of the heat pump in combination with MVHR (right). "PH" and "PrH" represent the post-heater and the pre-heater, respectively Siegele 2018

The unit can be installed in the façade or as a split system. The indoor unit (in which the condenser of the heat pump and the heat recovery system are placed) is installed in the kitchen (or alternatively could be integrated in the façade), while the outdoor unit contains the evaporator, the compressor and expansion valve of the heat pump. The air distribution system is placed in the corridor and supplies fresh air to the sleeping room, child room and living room. The air is extracted from bathroom and kitchen, cooled in the MVHR unit and its energy is used as source for the heat pump. An electric radiator is placed in the bathroom for comfort reasons. The heating system is controlled according to the operative temperature of a defined room (e.g. the corridor).

The evaporator of the heat pump is placed in the exhaust airflow after the heat recovery exchanger (HR) and uses the remaining energy of the exhaust air. The fresh supply air, pre-heated in a pre-heater and in the Heat Recovery Ventilation (HRV) or Energy Recovery Ventilation (ERV) exchanger, is heated in the condenser of the heat pump and, additionally, in a post-heater if the power of heat pump is insufficient, before to be supplied and distributed to the flat. The use of the ducts of ventilation system for the distribution of the heating power and the compact design represent the big advantages of this heating and ventilation solution. One of the limits of such a system is that air heating is coupled to the hygienic airflow rate and a room-wise control of temperature is possible only if electric radiator room-wise are additionally installed.

Supply Air Heat Pump with Secondary Air Recirculation

With an exhaust air-to-supply air heat pump (such as in a Passive House (PH) compact unit for ventilation, heating and DHW preparation) the heating power is limited by the hygienic flow rate and is usually 10 W/m² (the criterion for achieving PH Standard). If a renovation to PH Standard cannot be achieved (EnerPHit Standard for renovation allows 25 kWh/(m² a) corresponding to ca. 20 W/m² to 30 W/m²), either additional room-wise post-heaters have to be used or the volume flow has to be increased. The use of energy recovery membrane (ERV) offers the possibility to increase the volume flow and thus the heating power without violating the lower limit for the relative humidity. For equal relative humidity in the flat, the air exchange rate can be increased with ERV compared to a heat recovery ventilation (HRV), see Ochs et al. 2017a, Siegele et al. 2018. Alternatively, recirculation air can be used allowing to increase the heating power and enabling a more individual room control. The exhaust air after the heat/energy recovery of the ventilation system is the source of the heat pump and its performance is directly connected to the effectiveness of the heat/energy recovery. The effectiveness of the energy/heat recovery depends on the operation and boundary conditions (in particular the average relative humidity in the exchanger and the volume flow), which are strongly coupled to the building use and operation. By means of simulation these complex dependencies are investigated (see also Ochs et al. 2017b). The potential increase of the heating capacity and the aspect of air distribution inside the flat is investigated with a transient multi-zone approach including moisture buffer. This contribution discusses the different heat pump and heat distribution concepts and compares the performance.

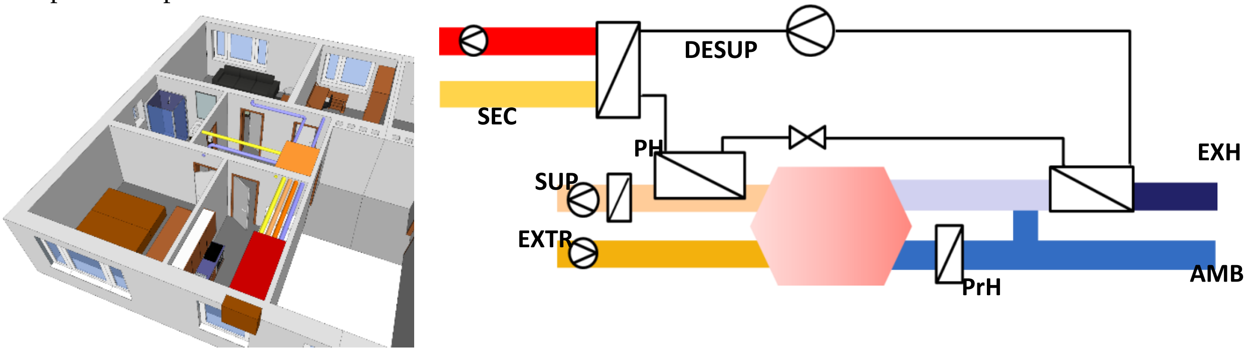

Fig. 3: 3D view of the flat with the supply air heat pump system with recirculation air in the corridor (left) and refrigerant cycle scheme (right). “PH” and ”PrH” represent the post-heater and the pre-heater, respectively. “DESUP” indicates the de-superheater that is used to heat the recirculation air in the corridor, (Siegele 2018)

FUNCTIONAL MODEL OF SUPPLY AIR HP WITH SECONDARY AIR RECIRCULATION

A functional model of an exhaust air heat pump with recirculation air was developed by the UIBK together with the company Siko Energiesysteme (see Fig. 4 and 5) and is investigated by means of laboratory measurements and building and HVAC simulations. A mock-up of a façade integrated outdoor unit was installed in the Passys test cell at UIBK for testing (see Fig. 5).

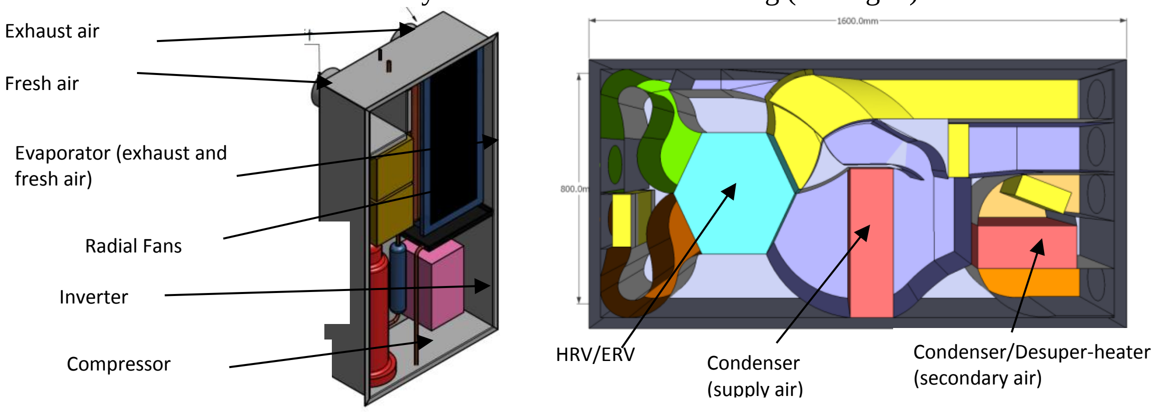

Fig. 4: 3D view of the outdoor unit with evaporator and compressor (left) and the indoor unit (right) with HRV/ERV, supply air condenser and secondary air condenser

Fig. 5: Outside view of the outdoor unit integrated into the prefabricated timber frame façade in the Passys test cell (left), outdoor unit in the laboratory at the UIBK (center) and indoor unit

MODELLING AND SIMULATION

Building Model

The building under consideration is a typical multi-story building Fig 1.) located in Innsbruck (annual average ambient temperature of 9.1 °C). It consists of five stories and two symmetrical flats for each storey. The staircase and the basement are not heated and a monthly average development for the ground temperature (annual average temperature of 14.9 °C) in considered. The reference flat (area of 70.9 m^2) considered here, is the flat of the first floor oriented to the Northeast side. The flat consists in six thermal zones (one for each room), while the others flats (below, above and adjacent the flat simulated), basement, staircase and ambient are boundary conditions in the simulation. Air exchange between two adjacent zones through the opening of the doors was modelled in Matlab/Simulink, based on an empirical model developed by Kopeinig et al. 2015.

A balanced mechanical ventilation unit with heat recovery (MVHR) supplies fresh air to the sleeping room (SL), child room (CH) and living room (LI) and extracts air from the kitchen (KI) and bathroom (BA). An air change rate of 0.07 [1/h] (constant throughout the year) due to infiltration through the façade is assumed.

Active cooling system is not considered. External movable shading blinds limit the solar gains during the summer and passive cooling of the flat is ensured by activation of night cooling ventilation and opening of the windows (see Ochs et al. 2018 for detailed information about the control strategies implemented).

The reference flat is occupied by three persons (ca. 24 m^2/person). The reference building is a residential building. It is assumed that the daily schedule of the occupation profile is valid also during the weekend. Additional information about the building model (e.g. internal gains, control strategies, wall constructions, etc.) can be found in Ochs et al. 2018.

HP Model

The performance of the supply air heat pump and supply air heat pump with secondary air recirculation were measured in the lab at UIBK. Based on these measurement results, in this study, performance maps of heating power and Coefficient of Performance (COP) of the heat pumps were simulated depending on the rpm of the compressor and ambient air temperature (see Figs. 6 and 7) . In case of supply air heat pump with secondary air recirculation system (Fig. 7), the heating power was split between the condenser (50%) and the de-superheater (50%) and an additional ambient air of 200 m^3/h were used as source, in addition to the exhaust air.

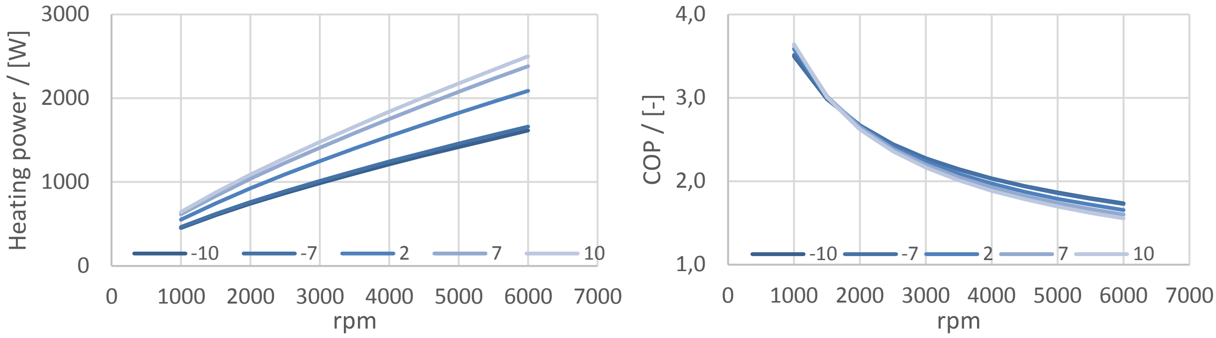

Fig. 6: Performance map of the thermal power of the heat pump (left) and the COP (right) depending on the rpm of compressor and ambient air temperature [°C] – Supply air heat pump system

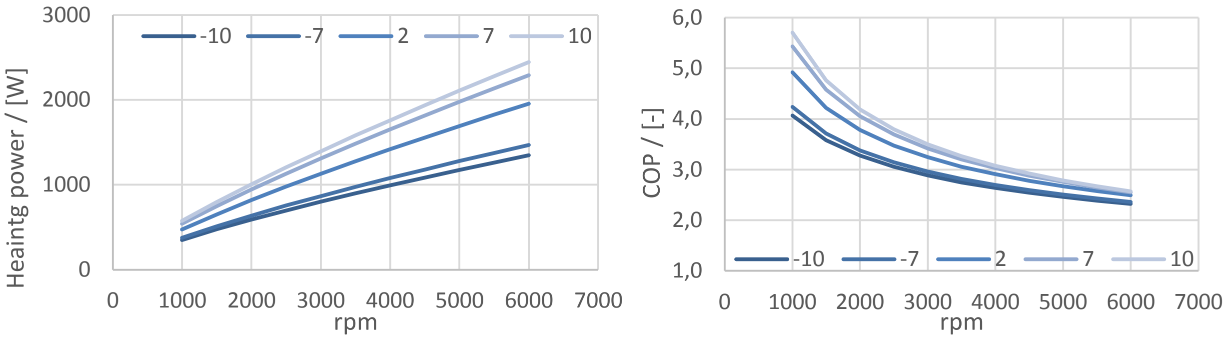

Fig. 7: Performance map of the total thermal power of the heat pump (left) and the COP (right) depending on the rpm of compressor and ambient air temperature [°C] – Supply air heat pump with secondary air recirculation system. Additional ambient air of 200 m3/h was used as source. The total heating power was split between the condenser (50%) for the supply air and the de-superheater (50%) for secondary air.

Reference Heating System

Electric radiator room-wise

In the framework of project "SaLüH!" innovative solutions for heating and ventilation for the renovation of small flats of MFHs are investigated and compared with regard to energy performance, thermal comfort and indoor air quality. The different heating concepts are analysed and compared against a reference system. Electric radiator room-wise system is characterized by low investments costs, but has high operating costs due to the inefficient use of electricity. In such a system, the room-wise control of the temperature as well as the independence of ventilation and heating systems are one of the most important advantages. In the building model, six electric radiators (one for each room of the flat, see Fig. 8, left) are used to keep an operative room temperature of 21 °C.

Split unit with recirculation air in the corridor

A variant of the electric radiator room-wise system is presented in Fig. 8 (right hand side). Recirculation air in the corridor (CO) is heated with a heat pump split unit and allows indirect heating (through heat transmission and air exchange) of the other rooms of the flat. Electric post-heaters (with a maximum power of 1000 W) are placed in all the rooms (except the corridor) to keep the operative temperature at the anticipated level, if necessary. Higher investment costs (compared to the direct electric heating system described above) due to the installation of the split unit must be considered, but a better performance can be expected and some cooling is possible in summer. In both systems heating and MVHR systems are separated and a room-wise control of temperature can be ensured.

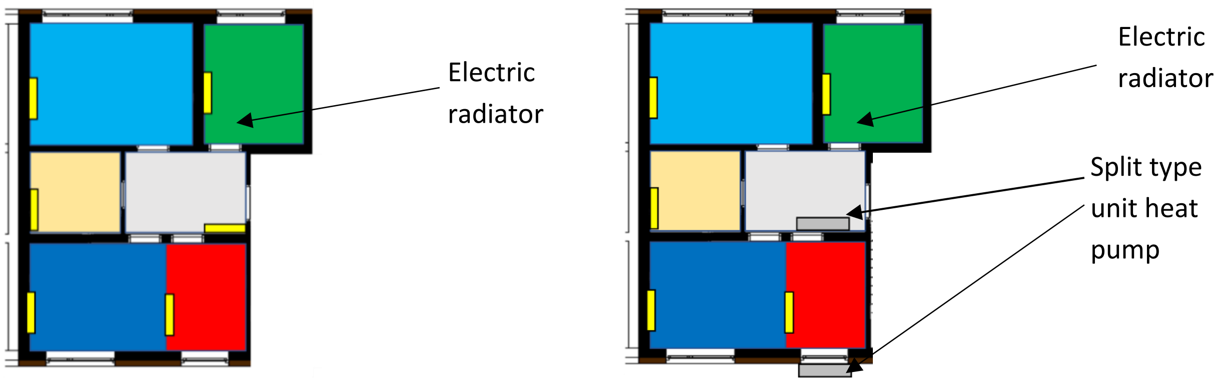

Fig. 8: 2D view of the flat with (left) electric radiators and (right) the HP split unit with recirculation of air in the corridor (Ochs et al. 2017). The indoor unit is installed in the corridor, while the outdoor unit can be integrated in the façade. All the rooms (except the corridor) are equipped with electric radiators

PERFORMANCE INDICATORS

Thermal comfort (T, r.H.), indoor air quality (CO_2) and performance of the proposed MVHR and HP systems are compared by means of simulation with the reference system. The following performance indicators are used:

$$SPF_{HP} = \frac{Q_{Condenser} + Q_{Desup}}{(W_{el,Compressor} + W_{el,Vsec} + W_{el,Vamb})} \quad (1)$$

$$SPF_{sys} = \frac{(Q_{HP} + Q_{Post-heater} + Q_{Radiator})}{(W_{el,HP} + W_{el,Post-heater} + W_{el,Radiator})} \quad (2)$$

$$SPF_{HRV} = \frac{(Q_{Pre-heater} + Q_{HX})}{(W_{el,Pre-heater} + W_{el,Fans})} \quad (3)$$

$$SPF_{tot} = \frac{(Q_{HRV} + Q_{sys})}{(W_{el,HRV} + W_{el,sys})} \quad (4)$$

SIMULATION RESULTS

Comfort and indoor air quality

Fig. 8 shows operative temperature of each room of the flat and the heating load versus the ambient temperature in the case of electric radiator room-wise system. This system is able to ensure optimal temperature distribution in each room because of the room-wise temperature control and can be assumed as base case to compare the four investigated systems. The flat requires a maximum hourly heating load of 1220 W (17.2 W/m^2), while during the summer night cooling and opening of windows are able to avoid excessive overheating of the flat with no need of active cooling systems.

In order to ensure good thermal comfort and indoor air quality (IAQ), relative humidity should not fall below the recommended values of 30% and the concentration of CO2 should remain below to 1200 ppm, respectively. The four heating concepts ensure these conditions and there are no significant deviations between the concepts. Fig. 8 (right hand side) shows the box plot of relative humidity and CO2 concentration of each room in case of electric radiator room-wise system.

As the electric radiator room-wise system, the split unit system gives the possibility to control independently each room of the flat and this leads to a good temperature distribution (see Fig. 10). Due to the coupling of fresh air supply and heat supply, overheating of supply air rooms occurs in case of the supply air heating system. Overheating in SL, CH and LI is avoided in case of secondary air recirculation, but improvement of control is needed to avoid under-temperature.

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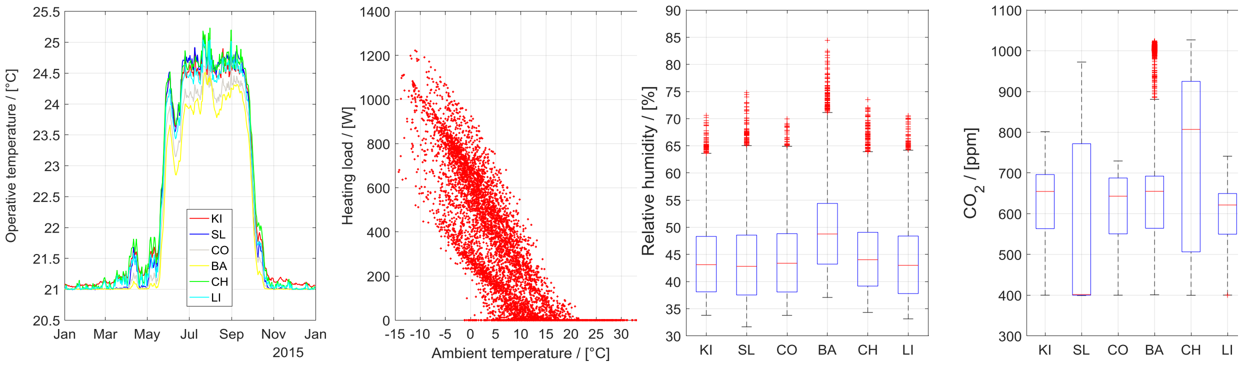

Fig. 9: Electric radiator room-wise system - daily average operative temperatures for each room of the flat (left) and hourly heating load versus ambient temperature (2nd from left); KI: Kitchen, SL: Sleeping Room, CO: Corridor; BA: Batch room; CH: child room, LI: Living room; Box plot of relative humidity (2nd from right) and CO_2 concentration (right) for each room of the flat; CO_2 ambient concentration is 400 ppm

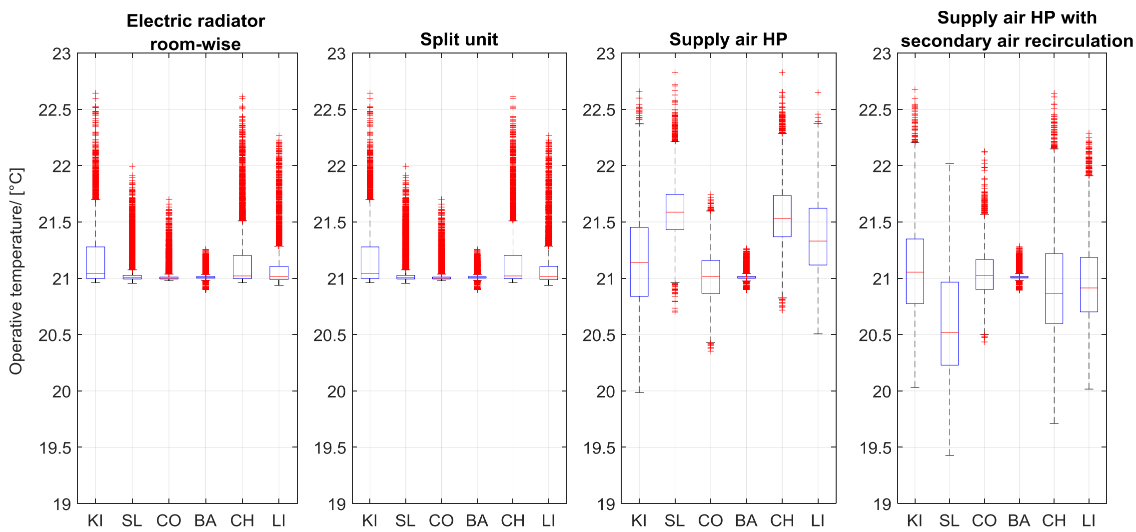

Fig. 10: Box plot of operative temperatures (hourly average) during the heating season for the four heating concepts

System performance

Table 1 shows the heating demand and heating load of the flat and electricity demand of heating system for the four investigated cases. Three different coefficient of performance (COP) for the split unit heat pump (i.e. 2, 3 or 4) were assumed in this simulation study (see system “B” in Table 1). The overheating of the supply air rooms (see SL, CH and LI in Fig. 10) in case of system C explains the slight difference in the heating demand (+ 3%) compared to system A. Similarly, system D presents lower heating demand (- 20%) because of the under-temperature of all the supply air rooms.

The performance evaluation of the four heating and ventilation concepts were performed through the definition of four SPFs according to the equations (1)-(4). In the definition of SPF_{HP} , the electricity consumption of the two additional fans for the secondary air (Specific Fan Power (SPF) of 0.093 Wh/m^3) and the additional ambient air (SPF= 0.0565 Wh/m^3) were considered, while $W_{el,Fans}$ in the definition of SPF_{HRV} indicated just the electricity consumption of the two fans for supply and extracted airflow rate (SPF=0.4 Wh/m^3). An additional electric power of 10 W was assumed for the cooling of the compressor of the heat pump through a fan.

The annual SPFs for the heating season for the four heating concepts are shown in T. SPF_{HP} is slightly higher in system D (2.45) compared to system C (2.43) because of the lower supply temperature of the heat pump. System C presents the highest SPF_{sys} (2.07) and this value is higher compared to system D (1.93) because of the lower electricity consumption for the heating of the bathroom. SPF_{HRV} is slightly lower for systems A and B (5.6) compared to heating concepts C and D (6.05 and 6, respectively) because of the higher $W_{el,Fans}$ for system A and B due to the slight longer heating period. SPF_{tot} is 3.2 for system D, slightly higher compared to system C (3.15) and much higher of system B (2.03), even in case a COP for split unit heat pump of 4 is considered.

Table 1: Annual heating demand (HD), maximum hourly heating load (HL) and annual electricity demand (ED) of heating system for the four heating concepts investigated.

	Electric radiator room-wise (A)	**Split unit (B)**	**Supply air HP (C**)**	**Supply air HP with secondary air recirculation (D**)**
HD / [kWh/(m²a)]	29.7	29.7	30.5	23.8
HL / [W/m²]	17.2	17.2	17.3	14.8
ED / [kWh/(m²a)]	29.7	27.1 / 26.3 / 25.9*	14.8	12.3

* in case of COP of 2, 3 or 4, respectively. ** The electric power of fan for compressor cooling (for system C and D) and for secondary air (for system D) are taken into account in the calculation of electricity demand

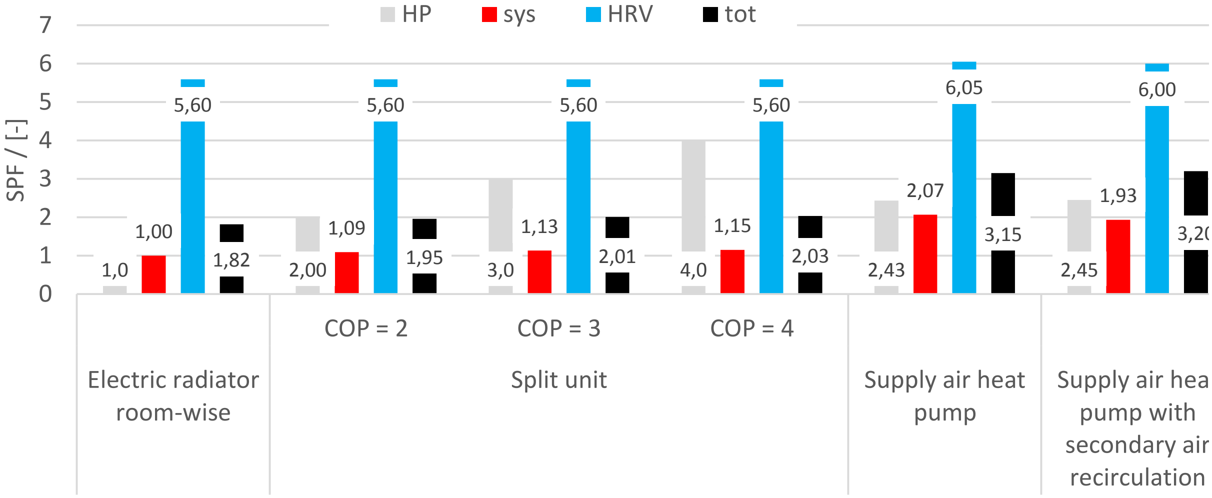

Fig. 11 Annual (heating season) SPFs of the heat pump ("HP"), heating system ("sys"), HRV and total HVAC ("tot"), according to equations (1)-(4)

CONCLUSIONS

In the framework of the Austrian project SaLüH!, four different heating and ventilation concepts were compared with regard to thermal comfort and energy performance to find efficient solutions for the renovation of small flats of MFH. All the systems investigated are able to ensure good indoor air quality in the flat and thermal comfort.

The innovative heating concept, based on a façade-integrated heat pump with secondary air recirculation, adds a new degree of freedom compared to the control of supply air heat pump system. The use of secondary air can limit the problem of overheating of supply air rooms during the heating season and allows to improve the energy performance of the heat pump (SPF_{HP} = 2.45) and of the whole system (SPF_{tot} = 3.2) compared to all the others three heating concepts. Control strategies can be further improved in order to avoid under-temperature of supply air rooms during the heating season.

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