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Renovation with an innovative compact heating and ventilation system integrated into the façade – An in-situ monitoring case study

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ABSTRACT

The very low heating load of deep renovated buildings following standards such as EnerPHit, and the limited space in renovation create the need for compact heating systems. An innovative heating and ventilation system - consisting of an exhaust air to supply air heat pump combined with a heat recovery ventilation unit, both integrated into a prefabricated timber frame façade - was developed and installed in a flat during the renovation of a multi-family house in Ludwigsburg, Germany. The system and the flat were monitored for the complete heating season 2016/2017. This paper presents: (a) an analysis of the monitoring data, (b) the development and validation of the models of the system and the flat, and (c) the results of the dynamic simulations that were performed for further system optimisation.

Inside the flat, good thermal comfort and indoor air quality conditions were achieved. The monitored SPF of the system was 2.8. Simulation results showed that with the optimised system and control, there can be an electricity savings of 25%.

The developed system has the potential to be cost-effective due to prefabrication and low heating capacity. It represents a compact solution with moderate energy performance, appropriate for minimally disruptive renovations.

1. Introduction

The building sector plays an important role in achieving the set target of fossil energy and CO_2 emissions reduction. In the European Union, the building sector share of energy consumption is 40% [1]. This is justified considering the fact that old, poor performing buildings dominate the existing building stock. For this reason, energy renovation has a high potential for energy savings. Within the framework of the European project iNSPiRe [2], energy renovation kits were developed aiming to simplify the renovation procedure while reducing costs, e.g. by prefabrication and façade integration of the heating, ventilation and air-conditioning (HVAC) system.

Passive renovation measures in buildings, such as the EnerPHit standard [3], are already well-known and established worldwide. The very low heating load of these buildings, in the range of 1 kW or even lower, poses an ideal scenario to apply very compact and cost efficient HVAC systems. The advantage of heat pumps compared to other technologies, such as gas boilers, is that they can be arbitrarily scaled down (in terms of heating power and size). Such compact heat pumps offer a high potential for a cost-effective plug-and-play-solution appropriate for deep renovations. Gustafsson et al. [4] compared the energy performance of three heat pump systems for a renovated single-family house through dynamic simulations. In the case of a building with low heating demand, a heat pump combined with HRV performed more efficiently than an exhaust ventilation system with either exhaust or ambient air-to-water heat pump and ventilation radiators. Kelly and Cockroft [5] compared a domestic air source heat pump to a gas boiler for terraced dwellings in Scotland resulting in 12% less carbon emissions, but 10% higher operating costs. In an experiment, Esen et al. [6] measured a solar-assisted ground source heat pump reaching a system COP of 2.88 using a horizontal ground heat exchanger.

Central heating systems are often not preferred in renovations of multi-family houses (MFH) [7] due to difficulties in reaching an agreement between the flat owners, and space limitations for the installation of ducts and pipes in common spaces. “Compact heat pump units” [8], which combine heating (optional cooling), ventilation, and hot water preparation, have been proposed as a decentralised solution. However, the available space inside the flats of MFHs could remain an issue. This space limitation can be solved through the development of new façade-integrated systems. In par-

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Nomenclature

BA	Bathroom
CDF	Cumulative distribution function
CHN	Children room with north orientation
CHS	Children room with south orientation
CO	Corridor
COP	Coefficient of performance
$\dot{C}$	Capacitance (mass flow times specific heat capacity), W/K
c_p	Specific heat capacity of air, J/(kg·K)
GF	Ground floor
HD	Heating demand
HRV	Heat recovery ventilation
HVAC	Heating ventilation and air-conditioning
HX	Heat exchanger
IAQ	Indoor air quality
KI	Kitchen
LI	Living room
$\dot{m}$	Mass flow, kg/s
MFH	Multi-family house
micro-HP	Micro-heat pump
P	Power, W
PI	Proportional-integral
Q	Thermal energy (heat), kWh
$\dot{Q}$	Thermal power, W
RMSE	root mean square error
SPF	Seasonal performance factor
W_{el}	Electricity, kWh

Subscripts

amb	Ambient air
exh0	Exhaust air after the HRV (see Fig. 1b)
exh1	Exhaust air after the evaporator (see Fig. 1b)
ext	Extract air
evap	evaporator
sup	Supply air
sup1	Supply air after the condenser (see Fig. 1b)
sup2	Supply air after the post-heater (see Fig. 1b)
min	minimum
sys	System composed of micro-HP, post-heater and electric radiator
tot	Total system composed of micro-HP, post-heater, HRV and electric radiator

Greek symbols

η	Heat recovery efficiency
ϑ	Temperature, °C

ticular, the combination of a heat pump with a ventilation heat recovery unit results in a highly efficient system. For example, Fucci et al. [9] measured such a system finding a COP of 9.5 at 0 °C. However, the high measured volume flow rate of 535 m^3/h makes the system unsuitable for a single flat. By simulating an air-to-air heat pump with and without heat recovery, Mortada et al. [10] concluded that the system performance increases significantly with heat recovery.

The present study focuses on an innovative HVAC system that consists of a so called micro-heat pump (micro-HP) and a mechanical ventilation unit with heat recovery (HRV). The objective of the paper is to prove the feasibility of the system, investigate its performance, and further optimise it. To the best of our knowledge, this is the first time that such a compact HVAC system has been integrated into a prefabricated façade. This system represents a decentralised solution (one unit per flat) for the renovation of MFHs aiming to minimise the space requirement inside the flat and to reduce investment costs through prefabrication and low heating capacity. A functional model of this system was installed in one flat, during the renovation of a MFH. A complete monitoring system was also installed to collect information on the performance of the HVAC system and on the comfort level inside the flat. The novelty of this paper lies in the collection and analysis of the monitoring data of the considered system for a complete heating period, combined with dynamic simulations for further system optimisation.

The structure of the paper is as follows. In Section 2, the core concept and the implemented methodology are described. Section 3 is divided into two parts. In the first part, the monitoring results from the first heating season (2016/2017) are discussed in detail. In the second part, the monitoring results are used to validate the simulation models; these validated models are then used to perform dynamic simulations for further system optimisation. Section 4 discusses the most important outcomes of this work, while Section 5 concludes the paper.

2. Concept and methodology

2.1. HVAC system

A micro-HP combined with an HRV unit was developed [11] within the framework of the European project iNSPiRe [2]. As seen in Fig. 1, the evaporator of the micro-HP is located in the exhaust air flow after the heat recovery exchanger, using the remaining enthalpy of the exhaust air. On the sink side, the condenser further heats up the supply air.

Even though the concept could be also compatible with radiators or floor heating, air heating was preferred as a distribution system since it represents a more compact and cost-effective solution (the ventilation supply ducts will be installed anyhow to improve IAQ). In an investigation of heating distribution systems for passive houses [12], it was found that air heating has the potential of 50% less investment costs compared to radiators and 60% compared to floor heating. Compared to radiators, which are controlled in each room with a thermostatic valve, air heating might lead to minor temperature difference among the different rooms. However, this should not be a concern in realistic scenarios. In-situ measured data have shown that already simple supply air cooling can be beneficial compared to split units in humid climates [13].

The functional model was designed for hygienic volume flow rates, i.e. between 90 m^3/h and 120 m^3/h (based on 30 m^3/h per person according to DIN 1946–6 [14]). An additional electric post-heater was placed in the central supply air duct to cover the peak building load. An electric radiator convector is recommended in the bathroom for comfort reasons. A commercially available ventilation unit (Pichler LG180) with a heat recovery efficiency of 85% (according to [15]) was selected, including a polymer membrane heat exchanger (HX) and a pre-heater for frost protection of the HX (position 5 in Fig. 1). A hermetic rotary compressor with a displacement of 5.72 cm^3 was placed in the supply air side, which allows recovering the thermal losses. In addition, the frequency control compressor aims to maximise the use of the remaining enthalpy of the exhaust air and improve the energy performance of the heat pump [16] (mainly due to high COP in low frequencies). Refrigerant R134a was used as it is common for such a low capacity compressors and the availability of compressors for alternative refrigerants is poor. The nominal power of the evaporator and condenser was 530 W and 740 W, respectively. A hot gas bypass was also installed (see Fig. 1) for defrosting the evaporator. The control of the defrost cycle was based on operation time and evaporator surface temperature; when the exhaust air temperature is below the set point for two hours, the defrost cycle operates for a period of 15 min.

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