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Prefabricated Timber Frame Façade with Integrated Active Components for Minimal Invasive Renovations

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Abstract

The objective of the EU-funded project iNSPiRe is to tackle the problem of high-energy consumption by producing systemic renovation packages that can be applied to residential and tertiary buildings. The renovation packages aim to reduce the primary energy consumption of a building to lower than 50 kWh/(m^2 a) for ventilation, heating/cooling, domestic hot water and lighting. The packages need to be suitable for a various climates in Europe while ensuring optimum comfort for the building users. One major aspect of iNSPiRe is the development of multifunctional renovation kits that make use of innovative envelope technologies, energy generation (including RES integration) and energy distribution systems. The technologies and renovation approaches developed by the iNSPiRe project will be installed and tested in three demo buildings. In this work the development, testing and modelling of a timber frame façade with integrated mechanical ventilation with heat recovery (MVHR) and a micro-heat pump (µ-HP) is presented. Three functional models were built for testing in so-called PASSYS test cells for the assessment of the thermal performance and for testing in the acoustic test rig at UIBK. Experimental results are used to validate a physical heat pump and MVHR model. The µ-HP with MVHR is a cost-effective and compact solution for ventilation and heating/cooling for buildings with high standard such as PH or EnerPHit. The integration of active components such as the MVHR and µ-HP in a prefabricated façade enables minimized space use and reducing installation time and effort.

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1. Introduction

The majority of existing building stock in Europe and worldwide is poor energy performance buildings and renovation plays a major role in achieving climate protection and energy independence. Deep renovation solutions in combination with integrated HVAC systems are developed within the framework of the European project iNSPiRe [1]. In this work the development, testing and modelling of a façade integrated micro-heat pump (μ-HP) in combination with mechanical ventilation with heat recovery (MVHR) is presented. Different functional models are developed in the framework of the EU-project iNSPiRe and are measured in PASSYS test cells (Passive Solar Systems and Component Testing) at the laboratory of Innsbruck University and will be later monitored in a demo building in Ludwigsburg, Germany. It is an example of social housing built in the 1970s, which contains 4 flats on 4 stories. During the renovation process a prefabricated timber frame façade will be fitted onto the building.

2. Motivation and Concept

The main objective of the development of a façade integrated micro-heat pump (μ-HP) is a cost-effective mechanical ventilation system with heat recovery (MVHR) in combination with a vapour compression cycle for heating and optionally cooling (μ-HP) for the application in very energy efficient buildings with a specific heating load in the range of 10 W/m² (such as PH or EnerPHit [2]). The exhaust air of the MVHR is the source of the μ-heat pump with a heating power of approx. 1 kW. A pre-heater (defroster) and backup heater for peak load coverage are required. For comfort reasons an additional bathroom radiator is recommended. Domestic hot water preparation is not covered, it can be provided e.g. using an additional DHW-HP. A simplified hydraulic concept is shown in Fig. 1.

a b c

Fig. 1. (a) Hydraulic scheme of the micro-heat pump; (b) photo of MHVR (Pichler) and evaporator (Siko Energiesysteme) (c), compressor and condenser (Siko Energiesysteme).

The ambient air (1) is heated with the defroster (5) if the ambient temperature drops below -3 °C (optionally -5 °C). The filter for the ambient air (6) is situated in front of the heat exchanger (16). The ventilator for the supply air (8) is situated after the heat exchanger. The supply air is heated in the condenser (13) of the micro-heat pump. If the temperature of the supply air after the condenser is too low to cover the heat load a post-heater (15) heats the supply air (3) up to 55 °C. The extract air (2) of the room is filtered (7) before the heat exchanger. After the heat exchanger the ventilator for the exhaust air (9) is situated. The compressor of the heat pump is situated in the air flow of the supply air before the condenser (13). The expansion valve (12) reduces the pressure between condenser and evaporator. Hot gas defrost (14) is necessary in case of ice formation in the evaporator (11).

3. Façade Integration

3.1. Advantages of Façade Integration

The prefabricated unit is designed as a compact system for façade integration and thus minimal space use. Façade integration offers several advantages (see the floor plan of the iNSPiRe demo building in Ludwigsburg in Fig. 2 as an example, the demo building is discussed in [3] in detail): (1) High degree of prefabrication, installation time can be kept as short as possible; (2) No additional space for MVHR and heating system is required; (3) Cold ducts (i.e. ambient air and exhaust air) are short and outside the thermal envelope; (4) Extract air ducts are completely placed inside the façade; the inlet of the extract air is placed in the reveal of the window; all ducts are prefabricated and part of the façade; (5) Installation with only one break-through and minimum installation inside the flat. With the µ-HP renovations with minimum intervention are enabled (minimum disturbance of tenants).

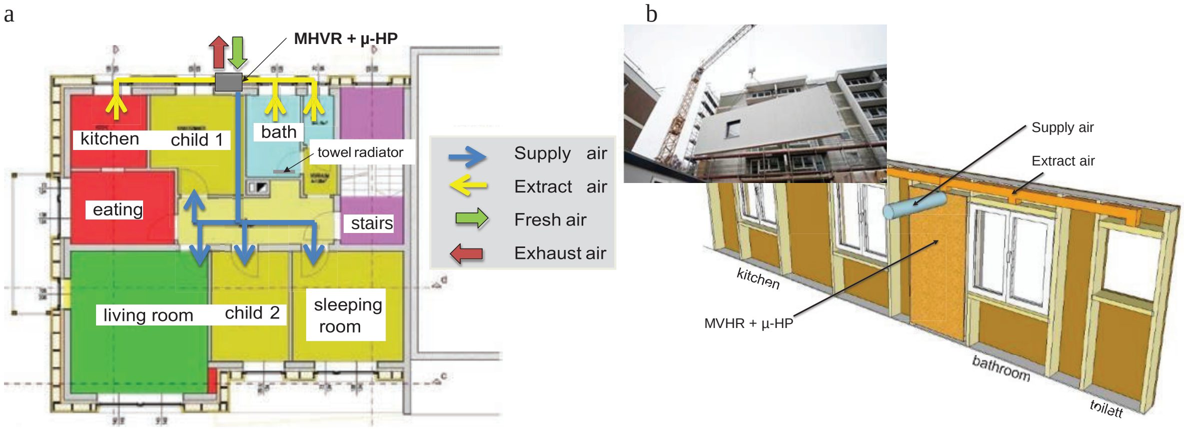

Fig. 2. (a) Floor plan of GF of demo building in Ludwigsburg (D) with position of the façade integrated MVHR with µ-HP; (b) integration of extract air ducts in the prefabricated timber frame façade and photo of a TES energy façade (Gumpp & Maier GmbH, e2rebuild.eu [4])

3.2. Aspects of Façade Integration

However, façade integration of active components is challenging. Several aspects have to be considered and problems in the following fields have to be solved: (1) Structural aspects (statics); (2) Building physics: U-value (thermal bridge), condensation risk, mold growth, sound (air- and structure-borne); (3) Fire protection; (4) Operation and Energy Performance (COP of MVHR & µ-HP considering thermal losses); (5) Condensate removal (MVHR and evaporator) and deicing (evaporator) – control; (6) Maintenance (in particular filter change) and repair (⇒ accessibility).

4. Functional Model, Measurements and Simulation

4.1. Functional Models

Different functional models of timber frame façades with integrated MVHR and micro-heat pump are developed in the framework of the EU-project iNSPiRe, see Fig. 3 and 4. In case of the first functional model (Fig. 3) the MVHR is integrated in the façade next to a window. A new type of silencer (compact silencer) with integrated filter which allows the maintenance from inside the building via the reveal is tested. Practical aspects of construction and accessibility are investigated. The second functional model (Fig. 4) is a façade with integrated MVHR unit and micro-heat pump. This functional model was primarily designed to measure the performance of the MVHR unit and of the micro-heat pump. For this reason no window was installed and the access to the ventilation unit and the heat pump is provided from outside. Furthermore, the reliability of the unit is tested and the control system is optimized.

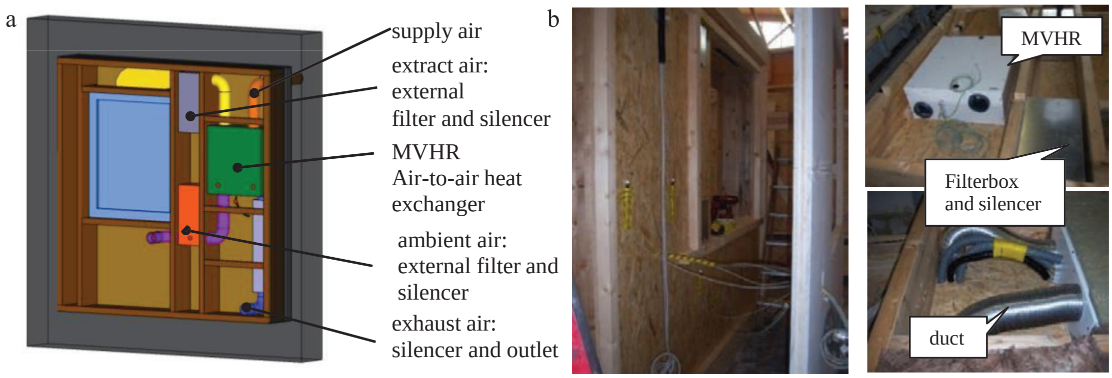

Fig. 3. (a) 3D Sketchup model and (b) photos of the first functional model (façade integrated MVHR), photos: Gumpp & Maier GmbH

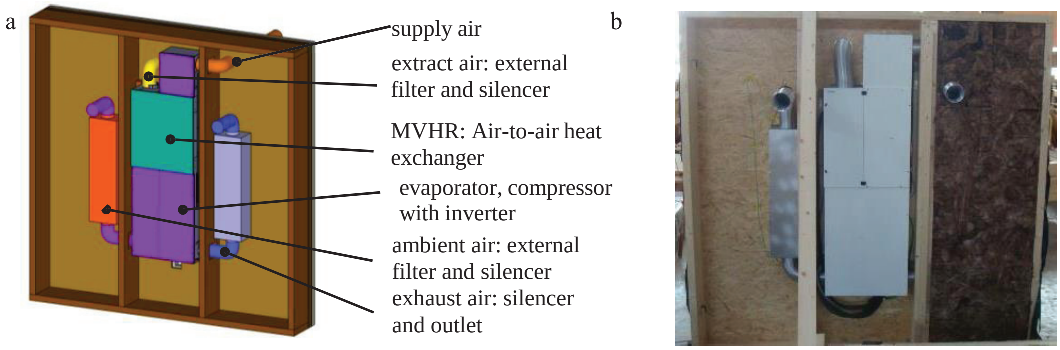

Fig. 4. (a) 3D Sketchup model and (b) photo of the second prototype (façade integrated MVHR and μ-HP), photos: Gumpp & Maier GmbH

The third functional model is used for the sound measurements of the MVHR and the micro-heat pump. Furthermore, it is used to optimize the façade-integration and to gain more experience within the prefabrication. The ducts and silencers for the extract, ambient and exhaust air will be integrated in the façade. It includes a window to measure the sound considering flanking transmission under realistic conditions.

4.2. Measurements

Outdoor lab measurements (PASSYS test cells, see Fig. 5 a and acoustic test rig Fig. 5 b) are performed to investigate aspects of building physics and to determine the energy performance of the MVHR and the μ-HP. The following parameters will be measured: building physics (U-Value, avoidance of moisture accumulation inside the construction and of mold growth, air-borne and structure-borne sound emission and sound insulation); energy performance of the active component (efficiency of mechanical ventilation with heat recovery η_{MVHRr}, COP (coefficient of performance) of heat pump and system). Acoustic measurements are in progress.

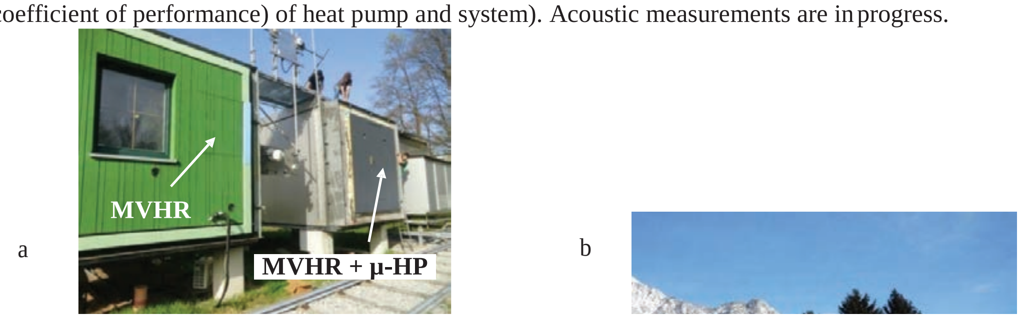

Fig. 5. (a) PASSYS test cell at UIBK with installed functional models, left cell: 1st functional model (MVHR next to window), right cell: 2nd functional model (μ-HP and MVHR) (b) acoustic test rig – photos: UIBK

4.3. Component Simulation

The development of the functional models are supported by component and system simulations. The measurement results are used to validate the simulation models. For the façade integrated MVHR thermal and hygrothermal simulations have been conducted on component level (2D/3D) and the system has been optimized to allow a secure operation. By means of lab measurements of the functional models these aspects are investigated in detail and simulation results are verified.

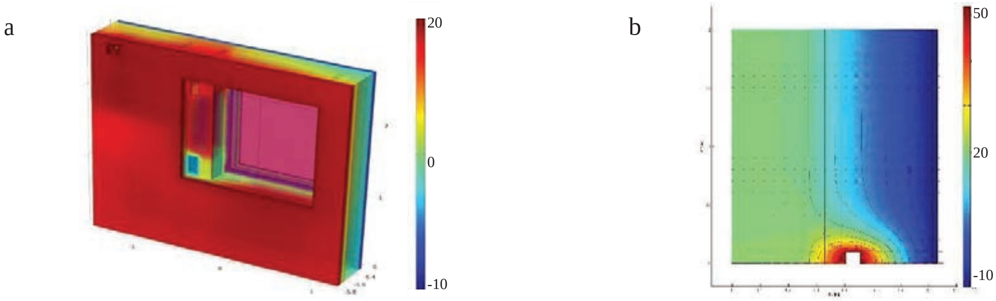

Fig. 6. (a) 3D model of the functional model for the characterization of the thermal and hygrothermal behavior (Comsol Multiphysics); (b) dynamic 2D model (Matlab) of façade integrated duct (thermal losses)

4.4. Physical MVHR and HP Model and HP Optimization

A physical MVHR and heat pump model has been developed based on Matlab/Simulink [5, 6]. It is validated against measurements (PASSYS test cells), see system COP in Fig. 7 a. The system COP includes the MVHR and the µ-HP:

$$COP_{sys} = \frac{(\dot{Q}_{MVHR} + \dot{Q}_{\mu-HP})}{(P_{ventilator} + P_{\mu-HP} + P_{control})} \quad (1)$$

With the validated model simulations are performed to optimize the µ-HP (refrigerant R134a instead of R290, other compressor fabricate, compressor position in supply air instead of extract air, evaporator size and fin distance, condenser size). With the optimized µ-HP (see Fig. 7 b) a performance map is generated for system simulation. Heat pump COP is in the range of 4 for low rpm and 2.4 for high rpm, almost independent from the ambient conditions (due to the MVHR). System simulations are performed for different building standards (PH + EnerPhit) in 7 different climates. The feasibility of the concepts could be proofed, see [7] for details.

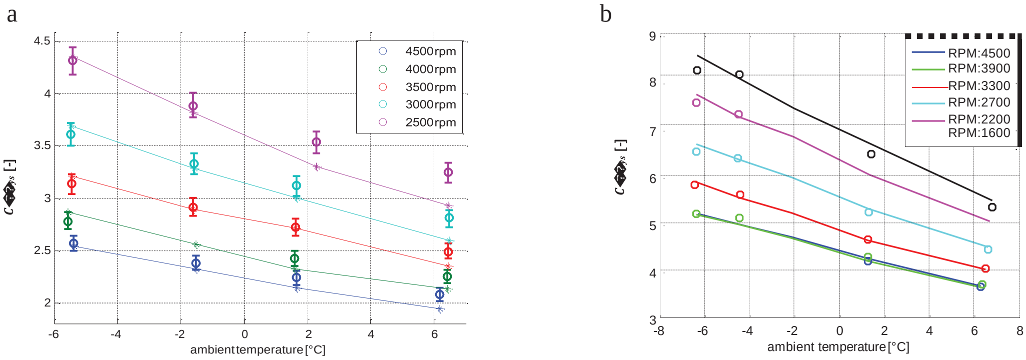

Fig. 7. (a) Measured and simulated system COP of first functional model with R290 [9, 10, 11] and (b) of second improved functional model

5. Limits of Façade integration

The façade-integration of the MVHR and micro-heat pump requires a wooden envelope with an insulation layer of 30 cm. The additional heat losses of the building due to the façade integrated component (thermal bridge) have been measured and calculated and are within an acceptable range ($\chi_{MVHR} = 0.22 \pm 0.1\ W/K$). Inaddition solutions for façade-integration of the extract air and of the supply air ducts are developed. Due to static reasons there are limitations for the dimension of the ducts integrated in the façade. As a consequence, relative high pressure losses can hardly be avoided. Due to the limited dimensions of the ducts, the pressure losses must be carefully calculated for each application. The external pressure losses (i.e. of ducts and silencers but without heat exchanger) should be limited to 50 Pa for each flow branch (ambient & supply and extract & exhaust) to avoid high electrical consumptions of the ventilators.

In case of air-heating high temperatures in the supply air (up to 55 °C) lead to relative high thermal losses. For a duct dimension of 50/200 mm (as used for the functional models and for the demo building in Ludwigsburg) and a wooden envelope with 24 cm a 3D FE simulations have been performed (see Fig. 6 b) to evaluate the influence of the heat losses on the design heat load of the micro-heat pump. The room temperature is assumed to be 20 °C, the ambient temperature 5 °C and the supply air 52 °C. The heat losses to the outside (ambient) are about 5 W/m and the heat flux to the inside (room) is 6.5 W/m for the steady-state case. However, due to the relatively high time constant of the construction (a step of the supply temperature from 20°C to 52 °C needs several days to reach steady-state conditions) for the design heat load the heat flux to the room must be considered as losses, too. Thus heat losses for the design heat load sum up to 11.5 W/m. Therefore façade integrated ducts for the supply air must be used very carefully and detailed design (using dynamic simulation) is recommended.

6. Outlook & Conclusion

The aim of this work is the development of a façade integrated MVHR with µ-HP which represents a cost-effective and reasonable efficient system for ventilation, heating (and cooling) for very efficient buildings such as Passive Houses or buildings renovated to EnerPhit standard. Functional models are tested in PASSYS test cells. Measurement results are used to validate a new simplified physical MVHR and heat pump model. Results of simulation studies show that the concept of the µ-HP is feasible. The micro-heat pump will be monitored in a demo building in Ludwigsburg. The µ-HP represents a cost-effective compact heating system for buildings with very high energy performance (new buildings as well as or for deep renovations) which - integrated in a prefabricated façade - can be applied with minimum space use and reduced construction and installation effort and time.

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