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The Effect of Exhaust Air Heat Pump on District Heat Energy Use and Return Temperature.

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Abstract

Deep renovation of apartment buildings in a cold climate requires ventilation heat recovery, while supply and exhaust ventilation with heat recovery and exhaust air heat pump are the two most commonly used solutions. Supply and exhaust ventilation distributes heating need evenly throughout the year, however exhaust air heat pump covers large part of heating need. The heat pump solution minimizes delivered district heat during warm periods, which increases heating district losses proportion in the heat produced in the plant. In addition a common exhaust air heat pump connection scheme increases district heat return temperature, which reduces the efficiency of heat plants e.g. in case of combined heat and power production. The purpose of this study was to compare the delivered district heat profiles of a typical retrofitted apartment building with the two ventilation heat recovery systems and to study the return temperatures of the heat substation. We modelled an apartment building to determine hourly power and supply/return temperatures of the radiator heating system and simulated the heat substation performance. Our study showed that an EAHP significantly affected the district heat consumption and return temperatures. Vast majority of DHW heating need was covered by the EAHP practically eliminating district heat consumption during summer and the return temperatures on the secondary side of heat exchangers increased. Therefore the used connection scheme of EAHP is disadvantageous for heating districts. The used method of heat substation model was effective and can be used to further study other possible EAHP connection schemes.

Keywords – energy retrofitting, district heat, ventilation heat recovery, heating system, exhaust air heat pump

1. Introduction

Renovating apartment buildings plays an important role in reducing primary energy use and carbon emissions. Deep-renovation to the energy performance level of new buildings is cost-optimal [1] and besides insulating building envelope proper heating and mechanical ventilation systems are needed to assure good indoor climate. In principle two ventilation systems allow reaching good energy efficiency and indoor climate – supply and exhaust ventilation with heat recovery (HRV) and exhaust ventilation with exhaust air heat pump (EAHP). Currently these two ventilation systems are accepted in the Estonian apartment building renovation grant scheme [2]. The HRV is more energy efficient and has lower global cost of the two [3], however it requires extensive construction works, is more expensive and therefore EAHP is also commonly used.

EAHP covers most of heat consumption during spring, autumn and summer, which in case of district heating increases the proportion of network losses in total production of the plant. In addition, depending on the EAHP connection scheme, the heat pump may increase the return temperature of heating district, which reduces the efficiency of some district heat plant types such as combined heat and power (CHP). On the other hand, the heat consumption of a building with HRV as a more evenly distributed heat consumption throughout the year and it has lower peaks, which makes it more suitable for district heat networks. Lundström and Wallin [4] showed using HRV is beneficial for a CHP plant and EAHP increases primary energy and carbon emissions due to increased electricity-to-heat ratio, whereas they did not take into account the increase in return temperature from the buildings. Rämä et al. [5] observed buildings before and after installation of EAHP and the increase of the return temperature to heating network was 0-10 °C, which depended on the connection scheme. They pointed out that this has a negative effect on CHP plants in addition to increased electricity use and decreased heat consumption.

The purpose of this study was to investigate the effect of exhaust air heat pump on the energy use and return temperature of a renovated apartment building. We simulated the energy needs of a typical deep-renovated Soviet era apartment building in Estonian with the two different ventilation types – HRV and exhaust ventilation with EAHP. We composed a heat substation model for both cases and simulated hourly temperatures on the secondary side of space heating and DHW heat exchangers.

2. Methods

A. Apartment building model

A typical 5-story concrete large panel apartment building from the period 1960-1980 was chosen to do energy simulations with well-validated dynamic simulation software IDA-ICE 4.7 [6] (Fig. 1). The building has 60 apartments, the net area is 3519 m^2 and heated area 2968 m^2. The building envelope is described in Table 1. Standard profiles from Estonian legislation [7] for building usage were used, which are given in Table 2.

Fig. 1 The model of a typical 5-story concrete large-panel apartment building built in 1960-1980. The middle floor results have been multiplied by 3.

Table 1. Description of building envelope

Area of walls above ground, m^2	1247.5
Area of walls below ground, m^2	162.9
Area of roof, m^2	611.9
Area of floor towards ground, m^2	640.7
Area of windows, m^2	523.0
Area of external doors, m^2	17.6
Specific heat loss of thermal bridges, W/K	198.8
Specific heat loss from infiltration[a], W/K	214.4

[a] – Constant infiltration was calculated using formulas 1 an d 2.

Table 2. The initial data about the building model.

Occupants, W/m^2	3[a]
Equipment, W/m^2	3[b]
Lighting, W/m^2	8[c]
Air flow rate, $l/(s\ m^2)$	0.42
Annual DHW consumption, l/m^2	520
Temperature setpoint in apartments	21
Temperature setpoint in staircases	16
Temperature setpoint in the basement	Unheated

[a] – Average daily usage factor of occupants was 0.6

[b] – Average daily usage factor of equipment was 0.6 and the heat gains were divided by 0.7 to calculate delivered energy

[c] – Average daily usage factor for lighting was 0.1

The constant infiltration rate was calculated with formula 1:

$$q_i = \frac{q_{50}}{3.6 \cdot x} \cdot A \tag{1}$$

where q_i is the infiltration air flow rate, l/s; q_{50} is the air leakage rate of building envelope at pressure difference 50 Pa, 3 $m^3/(m^2\ h)$; x is the factor taking into account the height of the building, 15; A is the total area of building envelope including the floors and walls connected to ground, m^2.

The specific heat loss of infiltration was calculated with formula 2:

$$H_{\mathrm{inf}} = q_i \cdot \rho \cdot c \tag{2}$$

where H_{inf} is the specific heat loss of infiltration air, W/K; q_i is the infiltration air flow rate, l/s; ρ is the densitiy of air, 1.2 kg/m^3; c is the specific heat of air, 1005 J/(kg K).

B. Renovation packages

The Estonian renovation grant scheme requires achieving energy performance class C i.e. calculated annual primary energy ≤150 kWh/m^2 [2] to receive a refund of 40% of the renovation costs. As the two studied ventilation systems had different efficiencies we had to use different insulation thicknesses and windows in the renovation packages to reach the goal. In case of HRV 150 mm of extruded polystyrene (EPS) was added to external walls and 300 mm of EPS to the roof. The case with EAHP required 200 and 400 mm of added EPS respectively. Besides, EAHP case required windows with lower U-value. The renovation packages are described in

Table 3. The supply and exhaust ventilation unit had an electric heater, so only radiator heating and DHW systems consumed district heat.

C. Building simulations

As a first step we created the building models with ideal heaters in the heated zones and made initial energy calculations to develop the renovation packages described in the previous section. The test reference year of Estonia was used [8]. During initial energy calculations the plant was not modelled, so we had to roughly assess how much exhaust air energy could be utilized

Table 3. The description of renovation packages

Renovation package no	1	2
Ventilation system type	HRV	EAHP
η/SCOP, %/-	80	3.0
Specific fan power, $kW/(m^3/h)$	2.0	0.8
EW U-value, $W/(m^2 \cdot K)$	0.19	0.15
Roof U-value, $W/(m^2 \cdot K)$	0.11	0.08
Window U-value, $W/(m^2 \cdot K)$	1.1	0.9
DHW tank volume, m^3	-	1.0

with the EAHP. The available energy in the primary side of EAHP was calculated so that exhaust air temperature would not drop below 4 °C and available energy was utilized as much as possible when there was an energy need in the space heating or DHW system. The seasonal coefficient of performance of the EAHP was assumed to be 3.0.

The next step was to calculate the heat losses at design outdoor temperature -22 °C and water radiator models with required capacity were added to the model. The design supply and return temperature was 70/50 °C, which is typical for renovated apartment buildings in Estonia. We made energy simulations with water radiator models and logged the parameters required for heat substation modelling with and hourly output time step, which were:

- Radiator heating supply and return temperatures
- Radiator heating system power
- The temperature and mass flow of extract air in case of mechanical exhaust ventilation

D. Domestic hot water profiles

Daily DHW consumption varies and we had to take it into account when modelling the heat substation. We used the daily profile developed by Ahmed et al. [9] and it is shown in Fig. 2. In addition the monthly DWH use also varies and the used yearly DHW profile is described in Fig. 3, which was also developed by Ahmed et al. [10]. The shown profiles were merged, inserted into the simulation software IDA-ICE, which calculated hourly DHW flow rates so that annual consumption was 520 $l/(s\ m^2)$ per heated area.

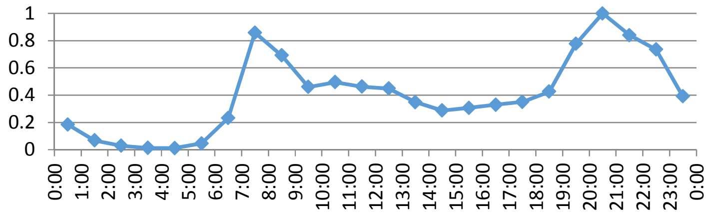

Fig. 2 Daily domestic hot water profile

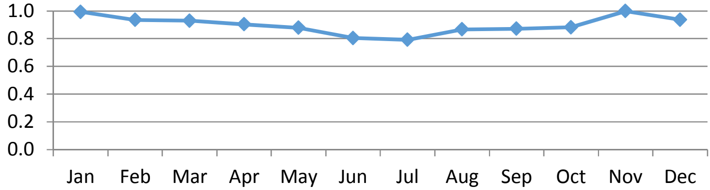

Fig. 3 Yearly domestic hot water profile

E. Heat substation simulations

The principle scheme of the studied district heating substation is described in Fig. 4. The piping and equipment drawn in black depicts a conventional substation and the part added after installing an EAHP has been drawn in red. In a conventional substation the motorized valves in the supply side of district heating network are controlled so that DHW temperature would be 55 °C and radiator heating supply temperature is kept at a level that is required according to outdoor temperature (Fig. 5). If an EAHP is added, then the heat pump primarily tries to maintain 55 °C in the DHW accumulation tank and secondarily the required radiator heating supply temperature. When the supply temperatures are not met, then the district heating valves are opened to meet the required temperatures.

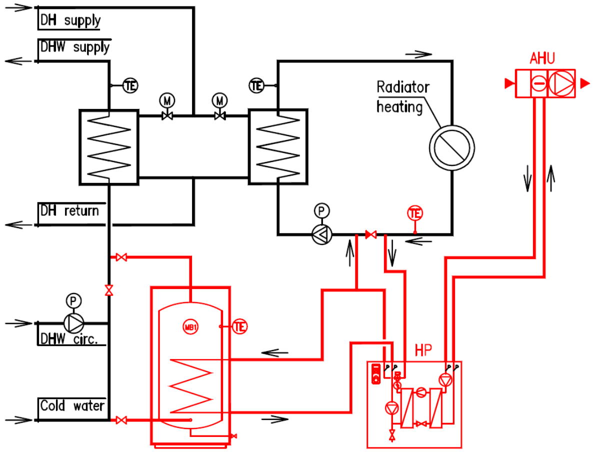

Fig. 4 Principle scheme of heat substation with EAHP. The piping and equipment added to a conventional district heat substation have been drawn in red. Code: DH – district heating; DHW – domestic hot water; HP – heat pump; AHU – air handling unit.

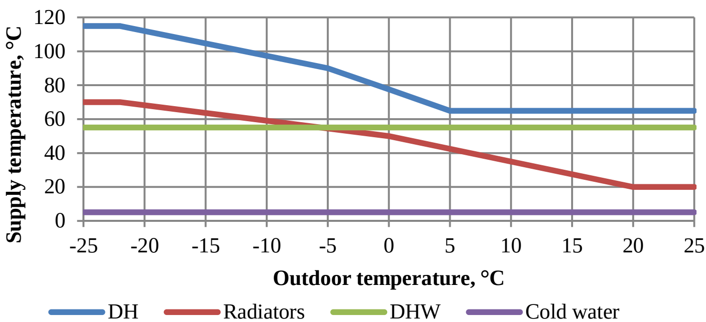

Fig. 5 Supply temperatures of district heating (DH), radiator heating, domestic hot water (DHW) and cold water depending on outdoor temperature

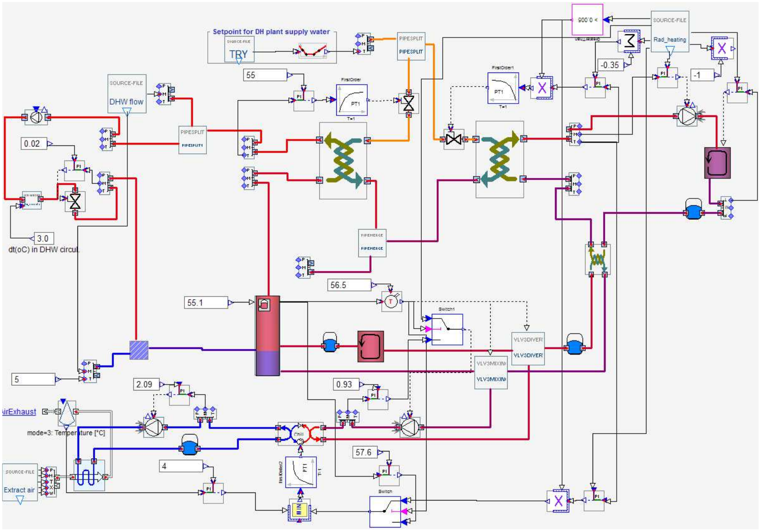

Fig. 6 IDA-ICE advanced level model of a heat substation model.

Fig. 6 illustrates the heat substation model of the station with EAHP. The information about radiator heating system, extract air, DHW flow rate and climate were inserted with source files. The EAHP-s task was to assure 56.5±1.0 °C in the DHW accumulation tank and the required supply temperature of the heating system. The district heating motorized valves were controlled so that DHW and radiator supply temperatures would be as required. DHW circulation had mass flow rate 0.02 kg/s and temperature drop 3 °C. The circulation pumps generally had constant mass flow rates, however the radiator heating pump maintained the mass flow rate defined in the source file and when the EAHP provided heat to the heating system, then its mass flow rate was identical to the heating system pump. The tank in the radiator heating system had a cooler, which assured the return temperature defined in the source file.

3. Results

F. Energy simulation results

The space heating needs of cases with HRV and EAHP were 28.7 and 77.6 kWh/m^2 respectively and main cause was supplying either preheated or cold outdoor air to rooms. The DHW heating need of both cases was 30.3 kWh/m^2. The delivered energy of the two studied cases differs significantly as can be seen in Fig. 7. The case with EAHP resulted in 2 times lower district heating energy, however the delivered energy of EAHP was similar to delivered heat. The HRV itself required more energy for fans and supply air heating compared to exhaust ventilation. The only systems that had identical energy uses in both cases, were electricity for equipment, lighting and heating need of DHW. The primary energy (PE) of cases with HRV and EAHP were 138.6 and 146.6 kWh/m^2 respectively which both fulfilled the 40% renovation grant requirement PE≤150 kWh/m^2 [2].

The hourly data required for heat substation modelling is given in Fig. 8 and Fig. 9. Fig. 8 provides the hourly data about radiator heating mass flow rates, supply and return temperatures. The case with HRV had significantly lower mass flow rates and also lower radiator heating return temperatures compared to the case with EAHP. Supply temperature was the same for all cases, because it depended only on outdoor temperature. Fig. 9 provides hourly extract air temperatures, which was generally around 21 °C during heating period and reached 29 °C during summer and mass flow rate that was approximately 1.8 kg/s throughout the year.

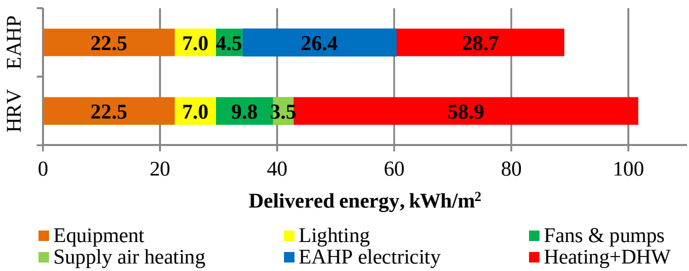

Fig. 7 The delivered energy of studied cases with HRV and EAHP respectively.

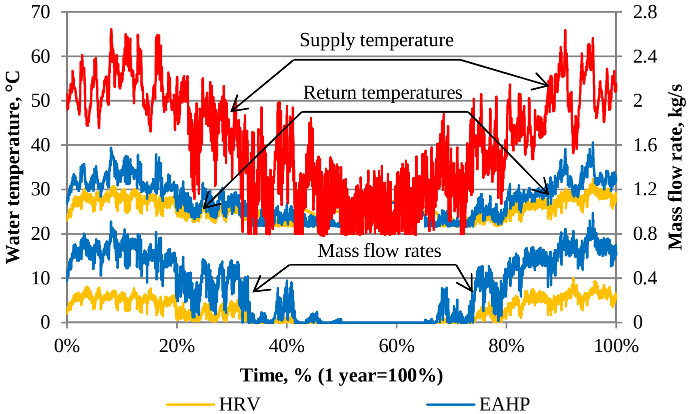

Fig. 8 The hourly radiator heating mass flow rates, supply and return temperatures of cases with HRV and EAHP.

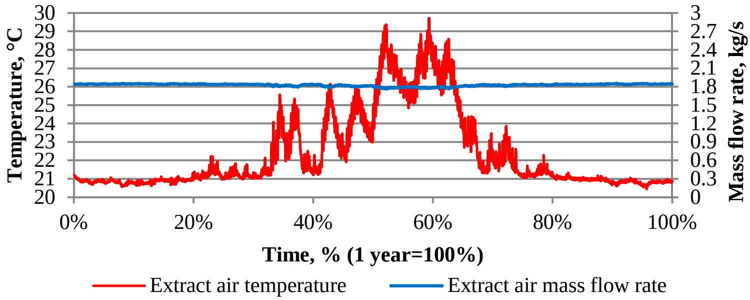

Fig. 9 The hourly extract air temperature and mass flow of the case with EAHP.

G. *Heat substation modelling results*

The used methodology for heat substation modelling resulted in similar heating energy use than building simulation without simulating the heat substation (Table 4 and Fig. 7). In case of the building with EAHP 99% of DHW need was covered by the heat pump, because DHW heating was the primary task. In addition 63.4% of space heating energy was covered by the EAHP.

Fig. 10 illustrates the return temperature on the secondary side of heat exchangers when there was any consumption from district heating network. The return temperatures of radiator heating system without EAHP increased

Table 4. The description of renovation packages

	Space heating			DHW		
	DH	HP	% of HP	DH	HP	% of HP
HRV	28.7	-	-	30.3	-	-
EAHP	28.9	48.9	62.9	0.3	30.8	99.1%

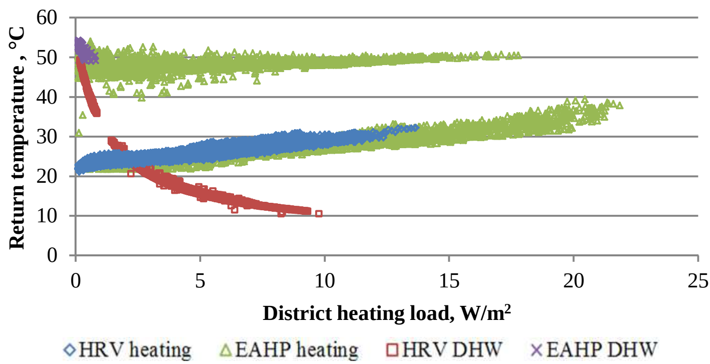

Fig. 10 The hourly heat exchanger secondary side return temperatures of heating and DHW systems depending on the district heating loads.

when the EAHP of the other case did not provide heat to the radiators (bottom group of green markers in Fig. 10). However, the return temperature increased by approximately 20 °C when the EAHP provided heat to the radiators (upper group of green markers). The temperature of cold water to the DHW heat exchanger decreased exponentially, when the consumption increased in case of a conventional heat substation. The drinking water temperature to the DHW heat exchanger was 50-55 °C, when the EAHP covered most of the energy need, however the district heating loads were low.

4. Discussion and conclusion

Our study showed that an EAHP significantly affected the district heat consumption and return temperatures. Vast majority of DHW heating need was covered by the EAHP practically eliminating district heat consumption during summer and the return temperatures on the secondary side of heat exchangers increased. Therefore the used connection scheme of EAHP is disadvantageous for heating districts. The used method of heat substation model was effective and can be used to further study other possible EAHP connection schemes, which might be more favorable for district heating and to optimize the size of accumulation tanks, heat pump and control algorithms. The modelled heat substation temperatures and mass flows should be used to quantify the EAHP impact on carbon emissions and primary energy with the goal to develop guidelines for integrating an EAHP to heating systems.

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