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Energy Balance of Compact Exhaust Air Heat Pump in a Single-Family House

Energetická bilance kompaktní větrací jednotky s tepelným čerpadlem v rodinném domě

The technology of exhaust air heat pump (EAHP) units and a brief classification of the products available on the market are presented in this paper. The performance of a compact EAHP unit providing exhaust air ventilation in a single-family house has been investigated. Due to the limited data provided by the manufacturers or by the 3rd party test reports, the laboratory testing of the EAHP unit has been performed. The data obtained from the test have been applied in the energy balance of the unit. A single-family house with a total heat loss of 5 kW was considered and the seasonal performance factor (SPF) achieved 2.5 for the given system with the compact EAHP.
Keywords: *exhaust air heat pump, ventilation, heat recovery, seasonal performance factor*

Článek představuje technologii kompaktních tepelných čerpadel využívajících odpadní vzduch a stručnou klasifikaci produktů dostupných na trhu. Předmětem zkoumání je konkrétní typ kompaktní větrací jednotky s tepelným čerpadlem zajišťující podtlakové větrání v rodinném domě. Kvůli malému množství dostupných dat z nezávislých testovacích protokolů nebo poskytovaných výrobci jednotek bylo provedeno laboratorní zkoušení. Získané parametry byly použity pro celoroční energetickou bilanci jednotky. Pro uvažovaný rodinný dům s celkovou tepelnou ztrátou 5 kW byl vyhodnocen sezónního topný faktor SPF celého systému na úrovni 2,5.
Klíčová slova: *kompaktní větrací jednotka s tepelným čerpadlem, větrání, rekuperace tepla, sezónní topný faktor*

INTRODUCTION

Nowadays, thermally well-insulated buildings have become a standard. The usage of high-performance envelopes, including windows, is emphasised and the importance of ventilation is slowly becoming an indivisible part of modern life. Ventilation systems with heat recovery from the exhaust air are also being used in single-family houses today. The question of heat recovery has been discussed since the 1970s already, especially in Scandinavian countries. Exhaust air heat pump (EAHP) units appeared as one option among all of them. The first EAHP units were only used for domestic hot water (DHW) preparation and with the function of space heating (SH) later on too. Today, compact EAHP units are mostly installed in northern countries, especially in Sweden and Finland. In 2018, more than 17 000 EAHP units were sold in Sweden, thus, sharing almost 30 % of the overall heat pump sales [2] and the share was around 90 % in new single-family houses [3]. Thanks to the favourable temperature of the indoor air, EAHP units have usually shown high efficiency values [4]. The operational conditions are relatively constant, which can positively affect the lifetime of the compressor used in the unit.

However, the topic of compact EAHP units is not a big issue in other European countries. An international standard for testing and evaluating the performance of EAHP units is still not available. The complexity of EAHP units also results in the fact that there is no common term for such types of heat pumps. The term EAHP is mostly used in northern countries and in English speaking countries. The German speaking countries from central Europe call it “heat pump ventilation compact units” or colloquially “compact units”. Finally, a universal and user-friendly tool for the evaluation of EAHP units in a specific installation for designers and building energy consultants is still missing today.

There are many different types of compact EAHP units with various designs, working with different temperatures at the evaporator and offering many functions. Different technologies of EAHP units are further listed. Specific EAHP unit devoted to a unidirectional exhaust air ventilation system has been further investigated from the point of view of its performance: laboratory testing, a simplified model development and energy balance calculation for a given single-family house. The energy balance has been undertaken using the bin method according to EN 15316-4-2 [1] with parameters derived from the laboratory testing.

EAHP UNITS

As mentioned before, there are many different types of EAHP units. In any case, the definition of EAHP units is fulfilled when the heat pump part is connected to the exhaust air path. Then, the EAHP units can be classified according to the following criteria.

- Heat source for the heat pump
  - Pure exhaust air
  - Mixed exhaust / outdoor air
  - Preheated air (e.g., ground heat exchanger)
- Distribution system
  - Air heating
  - Hydronic heating
  - Both possibilities
- Functionality
  - SH, DHW, ventilation
  - Optional cooling
  - Humidification
- Heat recovery exchanger
  - Included
  - Excluded
- Provided ventilation system
  - Balanced
  - Exhaust-only

Together, the last two points are the most interesting in the case of the EAHP efficiency evaluation. The presence of a heat recovery exchanger decreases the inlet temperature of the exhaust air at the evaporator and then the efficiency of the heat pump cycle is lower, but on the other hand, the heat exchanger improves the total energy balance of the ventilation. That is why the heat recovery exchanger must be included for, e.g., passive houses. In case of low energy buildings, retrofitting single-family houses or reconstructed flats EAHP unit with an exhaust-only ventilation system might be a solution. The cost of investments are significantly lower and the installation is much easier. An exhaust duct system can be situated in a very small space in the flat or house. The fresh air distribution is provided by a ventilation grid in the window frame or openable wall vents can be installed.

LABORATORY TESTING

A compact EAHP unit devoted to a unidirectional exhaust air ventilation system without a heat recovery exchanger has been investigated. The reasons for the choice were:

- the installation costs are lower when an exhaust duct system is installed only;
- the investment cost of the EAHP without the heat recovery exchanger with the exhaust fan only is lower as well.

The compact EAHP unit F750 from the Swedish manufacturer NIBE was chosen. The unit consists of a 180 l stainless steel DHW storage tank, a 35 l buffer tank for the SH, a 6.5 kW immersion electric heater, two circulation pumps and one exhaust air fan. Refrigerant R407c is used as the working fluid in the heat pump cycle. The declared heat output of the unit is 5.0 kW for the A20/W45 with an exhaust air flowrate 252 m^3/h at a maximum compressor speed.

The public data provided by the manufacturer are in accordance with European standards EN 14511-3 [6] or EN 14825 [7] in general. The points given especially by EN 14825 can hardly be used for the energy balance of the unit for a specific building, because the *SCOP* data and the power consumption are given for a building with a declared rated heat loss and no domestic water is considered in the *SCOP* evaluation. The data from the tests according to the conditions defined in EN 14511-2 [8] could be a good source for the further calculation and simulation with on/off heat pumps. Unfortunately, many manufactures do not publish detailed performance data (performance map) for different compressor speeds (frequency) and only some data are made public. It is not enough for development of the EAHP model. Third party independent certifications (e.g., HP KEYMARK or Q-label) do not provide the required data either.

In order to determine the detailed data on the heat output for the compact EAHP unit laboratory testing was performed in the laboratory of heat pumps at CTU UCEEB. The unit installed in the laboratory is shown in Figure 1. The principle scheme of the testing equipment is presented in Figure 2. The EAHP unit was placed into the laboratory climate chamber and connected to a hygrothermally conditioned space. The space heating loop of the EAHP unit was connected to a heat load circuit. The temperature difference at the condenser was controlled by an external speed-controlled circulation pump using a laboratory control system. The external air handling unit provided the air with the requested inlet dry bulb and wet bulb temperatures for the EAHP testing. The air flowrate at the evaporator was measured by a Sierra Nema mass flowmeter. The heating water flowrate at the condenser side was measured by a Siemens Sitrans Mag 5000 electromagnetic flowmeter. The temperatures were measured by Pt100 sensors. All the data for the performance evaluation were gathered by an ALMEMO data acquisition unit and by the control system of the laboratory. In order to evaluate the parameters of the refrigerant cycle, a ClimaCheck Performance Analyser was used.

Fig. 1 The EAHP unit in the laboratory

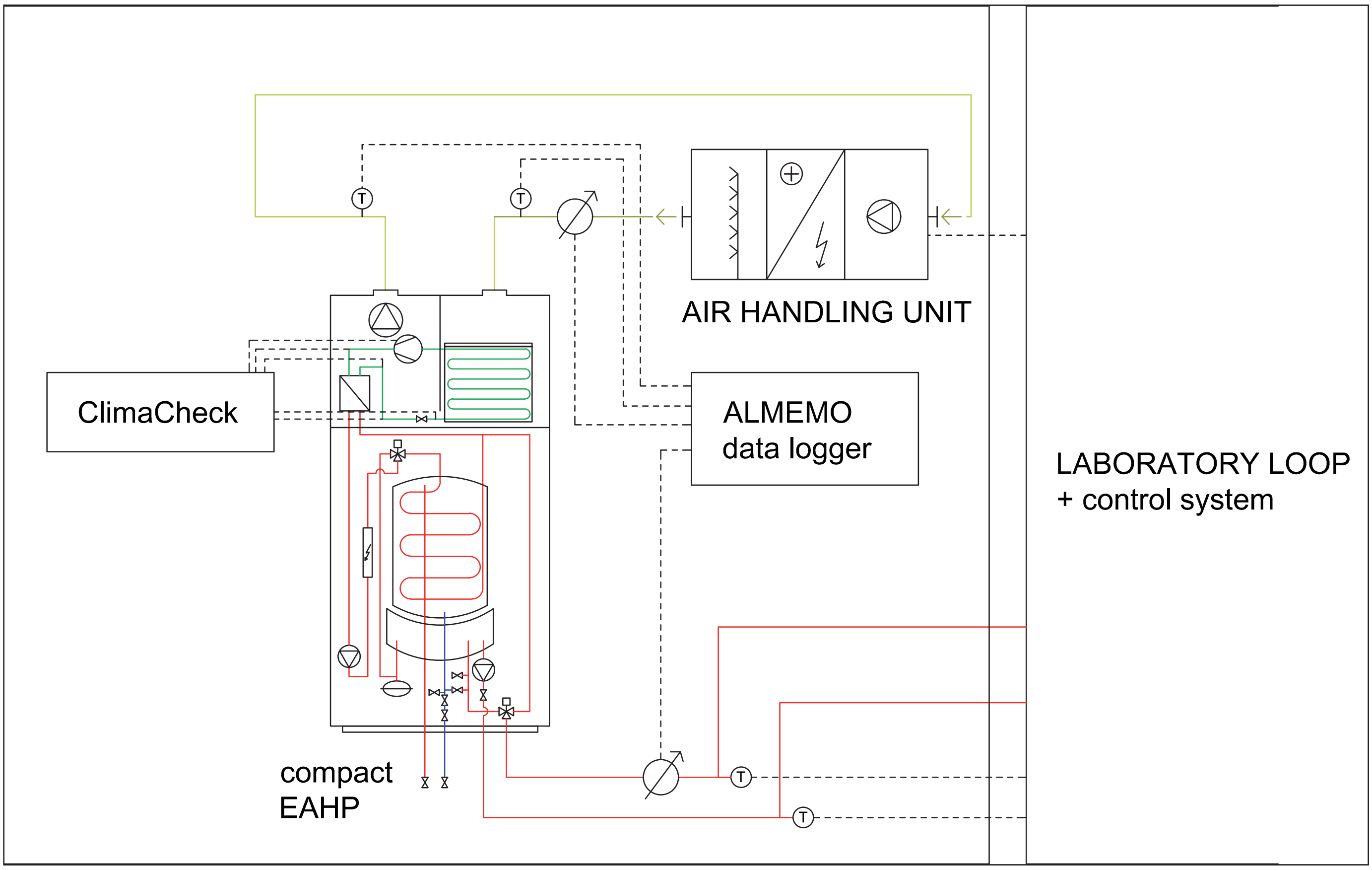

Fig. 2 The scheme of the EAHP testing

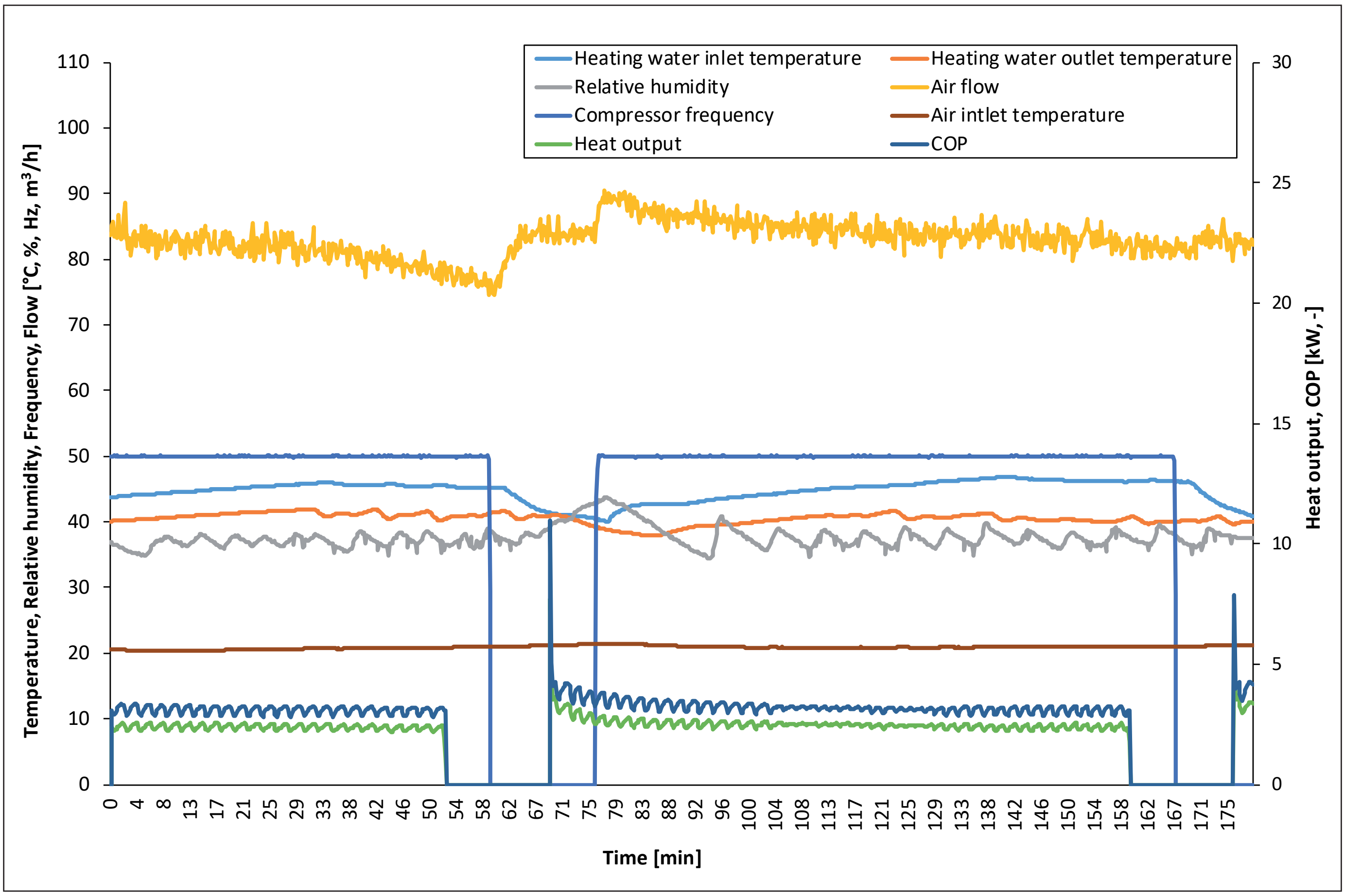

Fig. 3 A typical test cycle for the compact EAHP unit

Tab. 1 The performance data from the EAHP unit test for 240 m³/h

f_{HP} [Hz]	$\dot{V}_a$ [m³/h]	$T_{a,in}$ [°C]	$T_{a,out}$ [°C]	$\dot{V}_w$ [l/h]	$T_{w,in}$ [°C]	$T_{w,out}$ [°C]	E_{HP} [kW]	Q_{HP} [kW]	COP [-]
50	243	20.4	1.9	507	34.5	29.9	0.7	3.2	4.8
72	245	20.5	-7.9	698	35.5	29.9	1.1	3.7	3.5
50	243	20.3	6.0	581	45.2	40.0	0.8	3.6	4.4
72	238	19.4	3.3	749	45.4	40.1	1.0	3.9	4.1
50	239	18.9	6.5	580	54.0	50.1	0.9	2.8	3.0
72	239	18.5	0.9	686	55.4	50.6	1.4	3.9	2.8

The ClimaCheck unit measures the important values from the cycle, e.g., the condensing and evaporating pressure and temperature, the electric power input and provides the *COP* values of the cycle, refrigerant enthalpy, etc.

Different boundary conditions (test points) were set according to EN 14511-2 [8]. The exhaust air dry bulb temperature was 20 °C and the wet bulb temperature was 12 °C during the duration of the testing. The heating water temperatures at the condenser were maintained at 35/30 °C, 45/40 °C and 55/50 °C. The aim of the testing was to create a performance map with three different air flowrates – 80 (the minimum air flow required by the manufacturer), 180 and 240 m³/h and 4 different compressor frequencies: 25, 50, 72 and 100 Hz. Due to a large amount of test points, the testing periods were not fully in accordance with the test standard. However, at least 60 minutes of a steady state operation was required for each test point.

A typical test cycle is shown in Figure 3. Two defrosting cycles can be seen there. The air flowrate $\dot{V}_a$ [m³/h] decreases during the measurement. The flowrate depends on the frosting level at the evaporator and can decrease to 85 % of the original value. When the defrosting cycle starts, the heating water temperature decreases relatively quickly. Due to the heat output Q_{HP} around the value of 2.2 kW, it takes more than 70 minutes until a stable state is reached again.

The maximum heat output for 80 m³/h was 2.9 kW at the heating water temperatures of 55/50 °C and a frequency of 72 Hz. The *COP* reached 2.2 at the given conditions. It was not possible to test the EAHP unit at 100 Hz for the minimum air flowrate due to the evaporation temperature limit of -17 °C. The minimum heat output was 1.9 kW at W35/30 and 25 Hz with a *COP* = 4.5. Similar results for the higher air flows of 180 m³/h and 240 m³/h were obtained. The minimum heat output of 2.0 kW with a *COP* = 4.5 was reached for the flow of 180 m³/h at W45/40 and 25 Hz. The maximum heat output of 4.9 kW was reached at a 180 m³/h flow rate at W45/40 and 100 Hz with a *COP* = 2.6. An example of all the evaluated parameters for the air flowrate of 240 m³/h is presented in Table 1.

ENERGY BALANCE

To determine the annual performance of the compact EAHP unit in a single-family house, the energy balance according to EN 15316-4-2 [1] has been performed. The standard uses a bin method based on the frequency distribution of the ambient air temperature during the year. The energy balance is performed in temperature bins with the given temperature interval and duration of the ambient air temperature. As inputs for the bin method, the space heating and the hot water energy demand for the individual months are required together with a detailed performance map of the EAHP unit (frequency, heating water temperature).

A single-family house with a design heat loss of 5 kW (for an ambient air temperature of -12 °C and an interior air temperature of 20 °C) was chosen. A floor heating system was considered with the design heating water temperature difference of 35/30 °C and an equithermal control. The monthly space heating demand was calculated according to EN ISO 13790 [9] and the heat loss of the space heating system (distribution, emission) was considered to be 5 % of the theoretical heat demand. The annual heat delivered for the space heating Q_{SH} reached almost 12 MWh/a. In total, four people were considered with the DHW consumption of 40 l/day per person. The cold water temperature was 10 °C and the required tap water temperature was 55 °C. A hot water load decrease of 25 % during the summer months was also considered. The DHW energy demand was calculated according to EN 15316-3 [10] with a 30 % distribution heat loss. The heat Q_{DWH} delivered for

Tab. 2 The annual energy balance of the EAHP unit in the single-family house

Month	Q_{SH} [kWh]	Q_{DWH} [kWh]	Q_D [kWh]	Q_{HP} [kWh]	E_{HP} [kWh]	E_{SYS} [kWh]	COP_{HP} [-]	SPF_{SYS} [-]
January	1950	349	2299	1884	505	998	3.7	2.3
February	1662	315	1977	1669	450	829	3.7	2.4
March	1492	349	1841	1692	471	698	3.6	2.6
April	1054	337	1392	1392	410	484	3.4	2.9
May	613	349	962	962	324	387	3.0	2.5
June	0	337	337	337	171	186	2.0	1.8
July	0	262	262	262	132	144	2.0	1.8
August	0	262	262	262	132	144	2.0	1.8
September	576	337	913	913	311	376	2.9	2.4
October	1071	349	1420	1415	420	504	3.4	2.8
November	1488	337	1826	1633	455	723	3.6	2.5
December	1785	349	2134	1811	492	893	3.7	2.4
	11692	**3932**	**15624**	**14231**	**4272**	**6366**	**3.3**	**2.5**

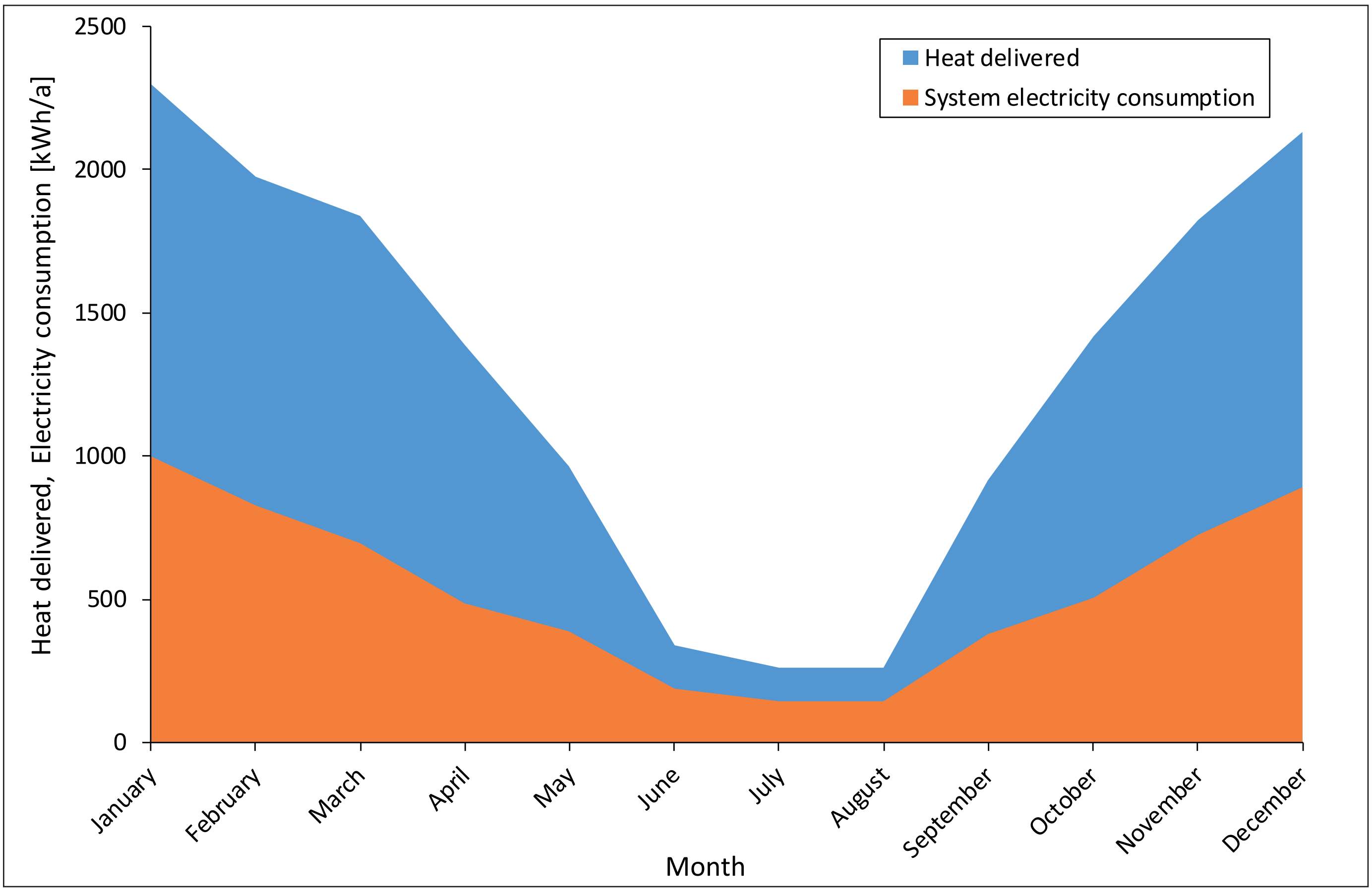

Fig. 4 The heat delivered to the house and the electricity consumption of the EAHP system

the DHW preparation results in a significantly smaller amount below 4 MWh/a were compared to the space heating.

The heat Q_{HP} delivered by EAHP unit itself covers about 91 % of the heat supply for the house, the rest is delivered by a backup electric heater. The total EAHP system electricity demand E_{SYS} includes the electricity consumption of the compressor, the unit's fans, the backup heater and the circulation pumps. The overview of the monthly energy balance is shown in Table 2. The comparison of the total heat delivered to the house with the electricity consumed by the EAHP system is presented in Figure 4.

CONCLUSION

An EAHP unit for a unidirectional exhaust air ventilation system without a heat recovery exchanger has been investigated. Due to the limited parameters available in the specifications for the modelling of the annual energy balance, detailed laboratory testing has been performed. The heat output and *COP* of the unit for the different temperature conditions, exhaust air flowrates and frequency of the compressor has been obtained. The annual energy balance of the EAHP unit operation in a single-family house based on the bin method has been evaluated. For the given example, the compact EAHP unit delivered about 91 % of the heat supplied by the system and the total *SPF* of the system resulted in 2.5. The EAHP unit performs with significantly better efficiency in the space heating application than for the domestic hot water preparation.

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