Equivalent Heat Recovery Effectiveness of Exhaust Air Heat Pumps

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Abstract

The concept of exhaust air heat pumps has been put forward decades ago. With the ongoing push towards drastic heat loss reductions in the residential systems, it is put forward again by simple exhaust ventilation manufacturers as an alternative for the traditional heat recovery with an air to air heat exchanger that is common in mechanical ventilation systems.

As with the latter form of heat recovery, the amount of effectively recovered energy is composed of different forms of energy, namely heat and power. The potential for exhaust air heat pumps, compared to air to air heat exhangers, is assessed by introducing the equivalent heat recovery effectiveness, combining both forms of energy into a single unit based on primary energy and consumer price.

Based on lab measurements of the performance of the heat pumps and assumptions on domestic hot water usage derived from both literature and field measurements, a dynamic model for exhaust air heat pumps in residential buildings was developed, providing detailed performance data for the assessment of the equivalent heat recovery effectiveness.

The results show that the equivalent heat recovery effectiveness for these systems is low. Based on the results presented, we conclude that a thorough assessment of the specific boundary conditions is necessary to assess the potential of exhaust air heat pumps in every single project.

Keywords – exhaust air heat pump; heat recovery; primary energy; price

1. Introduction

The concept of exhaust air to water heat pumps for the production of domestic hot water, using the exhaust air of a residential ventilation system as a source medium instead of ambient air, has been put forward decades ago [1, 2]. With the ongoing push towards drastic heat loss reductions in the residential systems, it is put forward again by simple exhaust ventilation manufacturers as an alternative for the traditional heat recovery with an air to air heat exchanger that is common in mechanical ventilation systems [3-5].

A review of such systems available on the Belgian market, found systems ranging 1.4 to 3 kW with a 200-300 l storage tank and a stated Coefficient of Performance (COP) of 3.4 to 3.8 under standard test conditions with 15 °C exhaust air temperature and heating the water to 45 °C from 8 manufactures [6]. For the production of domestic hot water, due to the risk associated with the development of the Legionella bacteria, of which especially the Legionella Pneumophila species is associated with the development of Legionellosis in human lung tissue, a temperature setpoint in the storage tank of 60 °C is usually maintained as a safety precaution. This has a considerable impact on the COP and it's seasonal average, known as the seasonal performance factor (SPF).

The fact that the amount of effectively recovered energy is composed of different forms of energy, namely heat and power, is an obstacle for a comparison of the performance exhaust air heat pumps and air to air heat exchangers. For this comparison, a conversion factor between both forms of energy has to be introduced. A wide variety of frameworks are available for the conception of such a factor, ranging from the simple ignoring of a difference between both forms of energy, over primary energy and exergy to operational cost [7]. Since primary energy is commonly used in energy performance requirements, operational cost represented by household consumer energy prices and primary energy are the most relevant for private users.

An additional problem is caused by the choice of reference system for domestic hot water production. Several popular system options, such as direct electric heating, a regular ambient air heat pump or a gas fired boiler will have a very different performance, depending on the framework used.

In this paper, the potential for exhaust air heat pumps, compared to air to air heat exchangers, is assessed by introducing the equivalent heat recovery effectiveness, combining both forms of energy into a single unit based on primary energy and consumer price for a number of simulations with different boundary conditions with all three 'classic' domestic hot water productions systems mentioned above as a reference. 2 case studies are reported as a reference for the simulation results.

2. Case Studies

Two exhaust air heat pump systems for the preparation of domestic hot water were monitored in different user modes. Both dwellings were heated during the monitoring period.

In the first case, a 1.6 kW heat pump with 290 l of storage capacity was monitored in a dwelling occupied by 2 mid-aged persons with an average domestic hot water consumption of 64 l/day. The monitoring period was during the winter of 2011-2012. Two user modes were selected for this case: direct electric heating with the internal electric resistance and exhaust air heat pump operation with a 62 °C setpoint.
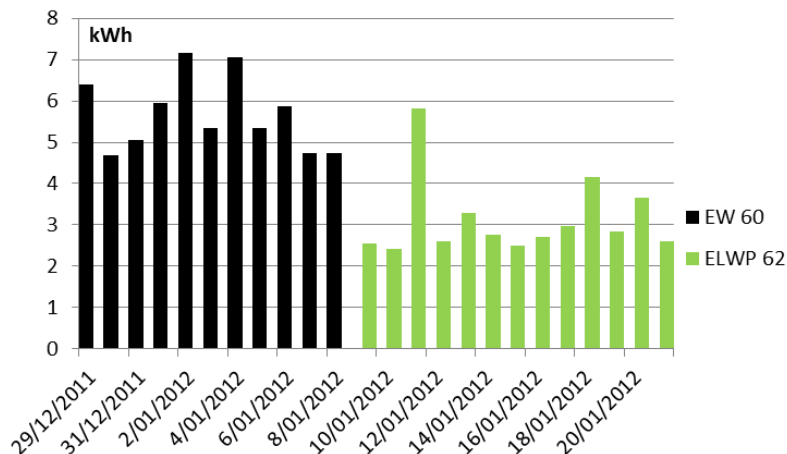
Fig. 1 Daily power consumption for domestic hot water production in case study 1 for the direct electric heating (EW) and exhaust air heat pump user mode (ELWP)

Comparing the power consumption of both user modes, of which daily averages are shown in Fig. 1, a specific Performance Factor of 1.8 was found. The average daily power consumption for both user modes was 5.7 and 3.1 kWh respectively.

In the second case, a 1.9 kW heat pump with 290 l of storage capacity was monitored in a dwelling occupied by 2 mid-aged persons and a young adult with an average domestic hot water consumption of 79 l/day. The monitoring period was during the spring of 2012. In this case, 4 user modes were selected for this case: direct electric heating with the internal electric resistance and exhaust air heat pump operation with a 62 °C setpoint, like in case 1 and 2 additional exhaust air heat pump user modes with 50 and 55 °C setpoints respectively. In the latter 2 cases, the water in the storage tank was additionally heated to 60 °C by direct electric heating. These two user modes were added because they are sometimes proposed as a method to improve overall performance of the system, since the heat pump, when operating, will be operating at a better COP. Comparing the power consumption of the different user modes, of which daily averages are shown in Fig. 2, a specific Performance Factor of 1.7, 1.9 and 2.2 was found for the 50, 55 and 62 °C setpoint modes respectively.
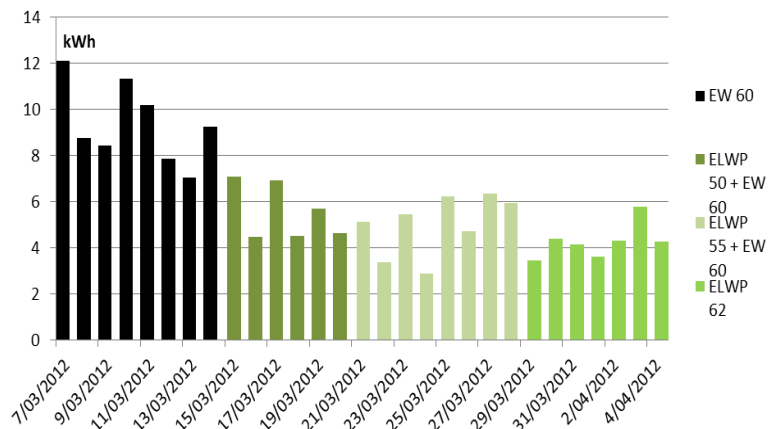
Fig. 2 Daily power consumption for domestic hot water production in case study 2 for the direct electric heating (EW) and exhaust air heat pump (ELWP) user mode with 50, 55 an 62 °C setpoint temperatures

The specific Performance Factors found in the 2 cases discussed above will be compared to Seasonal Performance Factors (SPF) calculated based on simulations in the subsequent sections of this paper. 12 case studies with electrically heated boilers were monitored for 2 weeks to establish a set of practical demand profiles for the simulations. The power consumption was continuously logged and the domestic hot water consumption was calculated based on the measured power consumption by eliminating the heat losses through the boiler tank wall. Table 1. lists the results of both for all 12 cases.

Table 1. average daily power and domestic hot water consumption in 12 case studies.

Case	Number of occupants	Energy (kWh)	DHW (l)
A	3	10.2	79
B	3	3.7	62
C	3	5.5	87
D	3	5.0	79
E	5	9.8	135
F	4	6.3	73
G	3	6.7	125
H	3	5.7	87
I	2	2.9	33
J	2	5.7	64
K	2	2.1	38
L	2	3.7	30

3. Modeling

In order to obtain a more general performance assessment of the exhaust air heat pump for the production of domestic hot water in dwellings, whole year simulations with a 15 minute time step were carried out on a reference dwelling [8] with a total exhaust air flow rate of 178 m³/h. The dwelling was continuously heated with a 20 °C set point and nightly setback to 18 °C.

From the 12 measured demand profiles for domestic hot water, Case D correlated best with the average of the total group, both in average value and form. This profile was therefore selected as demand profile to be used in the model. The climate date for Uccle (Belgium) was used. The temperature of fresh water from the grid was correlated with the outdoor temperature, varying between 10 and 16 °C over the course of the year, based on observations by the Belgian Building Research Institute (BBRI).

For each time step, the Coefficient of Performance (COP) was calculated based on the exhaust air temperature and the supply temperature of fresh water from the grid. The performance curve of a commercially available air to water heat pump was approximated with a 3rd degree function of both. The instantaneous power output of the heat pump is at each time step limited to assure that the temperature decrease in the exhaust air is lower than 15 °C. A constant set point temperature of 60 °C in the storage tank is used. In the basic scenario, a storage tank with a content of 300 l is modeled, corresponding to the storage capacity found in the case studies and in the models of exhaust air heat pumps for domestic hot water production found on the Belgian market. The insulated tank wall has a heat loss coefficient of 0.55 W/m²K. The number of occasions per year at which the temperature of the water during demand is below 35 °C is used as an indicator shortage of hot water.

4. Equivalent Heat Recovery Effectiveness

To assess the performance of exhaust air heat pump based domestic hot water production as a ventilation heat recovery measure, compared to air to air heat exchanger technology, an equivalent heat recovery effectiveness ε_{eq} (1) is proposed. ε_{eq} is defined as the ratio of the energy savings achieved by the exhaust air heat pump system in comparison to a reference system, converted to heat, and the ventilation heat losses.

$$\varepsilon_{eq} = (f_{ref} * Q_{ref} - f_{DHW} * Q_{DHW}) / (f_{vent} * Q_{vent}) \tag{1}$$

Where f is the conversion factor for the specific form of energy of the considered energy flux to heat in accordance with the chosen conversion framework. Q, gross energy use, is the product of the energy demand for that flux divided by its production efficiency.

5. Results

First, the power consumption and performance of 3 reference systems was calculated. These include a 3 kW direct electric heating system, an ambient air heat pump and a condensing gas boiler. For the ambient air heat pump, the same performance curve in function of air temperature and water temperature was used as proposed for the exhaust air heat pump, with a Seasonal Performance Factor (SPF) of 1.35. Since the temperature of the fresh water is always well below the temperature needed for efficient condensation of the flue gas, a constant efficiency of 0.85 is assumed for the gas boiler. The direct electric heating is assumed to have an efficiency of 1. Table 2. lists the domestic hot water consumption and gross energy use for the 3 reference systems for the basic scenario as well as that for the lowest and highest demand profile from the case studies.

Table 2. Domestic hot water (DHW) consumption and gross energy use for the direct electric heating system (DEH), ambient air heat pump (AHP) and condensing gas boiler (CGB).

Profile	DHW	DEH	AHP	CGB
Basic	79 l/day	1934 kWh	1428 kWh	2275 kWh
Low	30 l/day	1101 kWh	813 kWh	1295 kWh
High	135 l/day	2839 kWh	2096 kWh	3340 kWh

For the basic demand profile, the 3 user modes monitored in case study 2 were simulated for the exhaust air heat pump system, achieving total Seasonal Performance Factors (SPF) of 1.15, 1.21 and 2.96 for the 50, 55 and 62 °C set point respectively.

The SPF of the first 2 user modes is inferior to that of the ambient air heat pump system due to the relatively large portion of energy supplied by the electric heater in these scenarios (SPF = 1). The size of the storage tank causes the water temperature to remain above the heat pump set point except at peak demand, thus seriously restricting the operating time of the heat pump. During operation, the heat pump achieves a SPF of 3.93 and 3.43 respectively. In all scenarios, the number of hot water shortages is lower than 5 per year. Selecting a smaller storage tank (150 l) improves the total SPF of the lower set point user modes to 1.41 and 1.57, but increases the number of shortages. For the 'High' demand profile, total SPF with a small storage tank is 1.48 and 1.96 but the number of shortages reaches an unacceptable 80 instances.

The equivalent heat recovery effectiveness is calculated for the three references with primary energy and operating cost as conversion framework. The production efficiency for heat taken into account in the gross ventilation demand is 0.85, identical to that used for domestic hot water production. The conversion coefficients between electrical energy and heat considering the whole EU for both frameworks are virtually equal: 2.75 and 2.81

respectively. Therefore, only the results for primary energy are listed in table 3.

Table 3. equivalent heat recovery effectiveness with direct electric heating system (DEH), ambient air heat pump (AHP) and condensing gas boiler (CGB) as a reference for the 3 demand profiles and primary energy as a conversion framework.

Profile	DEH	AHP	CGB
Basic	0.45	0.27	0.06
Low	0.26	0.16	0.04
High	0.66	0.40	0.09

6. Conclusion and Discussion

The equivalent heat recovery effectiveness found for exhaust air heat pumps for domestic hot water production are generally low. An acceptable heat recovery efficiency was only found when high domestic hot water consumption was assumed and direct electric hot water production was used as a reference system. When a gas boiler is considered as the reference system, the equivalent heat recovery effectiveness is lower than 10% in all cases. Based on these results, exhaust air heat pumps for domestic hot water production can't be considered an efficient ventilation heat recovery system.

In this paper, only exhaust air heat pumps for domestic hot water production in residential exhaust ventilation systems were considered. In situations where other, higher temperature sources media for the heat pump are available, the Seasonal Performance Factor (SPF) will increase and therefore the equivalent heat recovery effectiveness could become more competitive to other technologies. The same observation can be made if the set point requirement for domestic hot water, necessary for the mitigation of the risk of legionella development, can be lowered [9]. In case the set point temperature can be lowered to 55 °C, the SPF will increase by 15%, increasing the equivalent heat recovery effectiveness in the basic demand profile scenario with 3 pp.

An additional consideration to be taken into account when assessing the performance of exhaust air heat pumps for domestic hot water production is that the additional fan energy required for air to air heat exchanger operation. With an additional specific fan power (SFP) of 2000 J/m³ (SFP 3) [10], a classic heat recovery effectiveness of 0.85, the EU average of 3067 Heating Degree Days [11] and a primary energy conversion coefficient for electricity of 2.75, the equivalent heat recovery effectiveness of an air to air heat exchanger is only 31%.

A thorough assessment of the specific boundary conditions is therefore necessary to assess the potential of exhaust air heat pumps in every single project.

7. Acknowledgment

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