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ANALYSIS OF THE ON-SITE PERFORMANCE OF A MINI EXHAUST AIR HEAT PUMP INTEGRATED INTO A LOW ENERGY DETACHED HOUSE SITUATED IN BELGIUM

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ABSTRACT

Nowadays, the building sector accounts for 40 % of the total EU energy consumption. In that context, the construction sector is today on a critical path to help decarbonize the European economy by 2050. For this purpose, sustainable cooling and heating technologies should be developed and on-site measurements may confirm the performance measured under laboratory conditions.

This paper presents the analysis of the on-site performance of a mini exhaust air heat pump integrated into a low energy detached house situated in Belgium. The system consists of five components: a simple exhaust ventilation system, an exhaust air heat pump, a backup electrical resistance, a domestic hot water storage tank and fan-coil units to heat the building.

In that system, the heat source of the heat pump is the air from the ventilation system and the heat pump heating capacity is limited to 1400 Watts. The totality of the domestic hot water is produced by the heat pump but only a fraction of the space heating demand is covered by the machine. For this reason, this machine is particularly suitable for apartment buildings characterized by a low space heating demand and a significant energy demand related to domestic hot water production.

In the first part of the paper, the characteristics of the building case study and the different components of the system are presented.

The second part of the paper describes the sensors placed in the building used to measure the on-site performance of the machine.

Lastly, the on-site performance of the machine is presented. The influence of the main variables (exhaust water temperature, supply air temperature, outside temperature, etc.) on the performance is also discussed.

KEY WORDS: Exhaust air heat pump, on-site performance

1. INTRODUCTION

Buildings are responsible for 40% of energy consumption and 36% of CO2 emissions in the EU [1]. In order to reduce this energy consumption, the European Commission proposed two Directives: the Energy Performance of Buildings Directive [1] in 2010 and the Energy Efficiency Directive [2] in 2012. In that context, Member States need to make significant efforts to improve the energy efficiency of buildings.

Two key measures are generally implemented: an increase of the thermal insulation and the improvement of the airtightness. As a result, a mechanical ventilation is required to ensure a good indoor air quality and the ventilation has a more significant impact on the building energy consumption, accounting for 30 to 60% of the total building energy use ([3] and [4]). For these reasons, a mechanical ventilation system with a highly efficient heat recovery is installed in the majority of new and retrofitted residential buildings.

This paper presents the on-site performance of a mini exhaust air heat pump that is combined with a simple exhaust ventilation system. In that system, the heat source of the heat pump is the exhaust air from the ventilation system and the heat pump heating capacity is limited to 1400 Watts. The totality of the domestic

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hot water is produced by the heat pump but only a fraction of the space heating demand is covered by the machine. For this reason, this machine is particularly suitable for apartment buildings characterized by a low heating demand and a significant energy demand related to domestic hot water production.
The first part of the paper details the characteristics of the building in which the heat pump is installed. The different components constituting the ventilation and the heating systems are also presented.
In the second part of the paper, the sensors, located in the building and used to measure the on-site performance of the machine, are described
The last part of the paper presents the on-site performance of the machine. The electrical consumption and the heating capacity of the machine in domestic hot water production mode are discussed. The global electrical consumption of the building and the influence of the main variables (outside temperature, etc.) on the performance are also discussed.

2. DESCRIPTION OF THE SYSTEM

2.1 Building characteristics

Geometry. The building case study consists of a new residential building built in 2016. It is a wooden two-story freestanding house whose geometry is typical of new residential buildings in Belgium. An unoccupied attic is also included into the heated volume. The total floor area is 155 m², the total heated volume is 583 m³ and the total exposed area is 389 m². The n_{50} value is estimated to be 0.6 vol/h. Table 1 shows the floor areas for the different rooms of the building.

Table 1: Floor area for the different rooms

	Room	Floor Area [m²]		Room	Floor Area [m²]
Ground floor	Living room	35	First Floor	Bedroom 1	19
	Open kitchen	13		Bedroom 2	16
	Office	13		Unoccupied room 1	12.5
	Laundry room	8		Unoccupied room 2	6
	Toilet	1.5		Bathroom	11
	Entrance hall	7		Night hall	13
	Total	77.5		Total	77.5

Building envelope. The building envelope is light and respects the most recent standards in terms of thermal insulation. In fact, it is a wooden structure insulated with 40 cm of sprayed cellulose for the roof and the outer walls. Furthermore, the concrete slab floor is insulated with 65 cm of cellular glass. Finally, the windows consist of triple-glazed windows with aluminum frames with thermal breaks. The global heat transfer coefficient of the building is equal to 0.2 W/m²-K and the K-level (as defined in the Belgian Energy Performance of Buildings Directive [5]) is equal to 17. Table 2 summarizes the U-values for the different types of walls. The building is consequently efficient from the energetic point of view.

Table 2: U-values for the different types of walls

Wall type	Composition	Area [m²]	U-value [W/m²-K]
Outer wall	Wood structure + 40 cm cellulose	139	0.11
Roof	Wood structure + 40 cm cellulose	127.2	0.15
Floor	Concrete slab floor + 65 cm cellular glass	82.7	0.07
Window	Triple-glazed + aluminum frame	18.5	0.84

2.2 Description of heating, ventilation and air-conditioning systems

This section describes the heating, ventilation and air-conditioning systems installed in the building. Figure 1 shows a simplified representation of the HVAC systems.

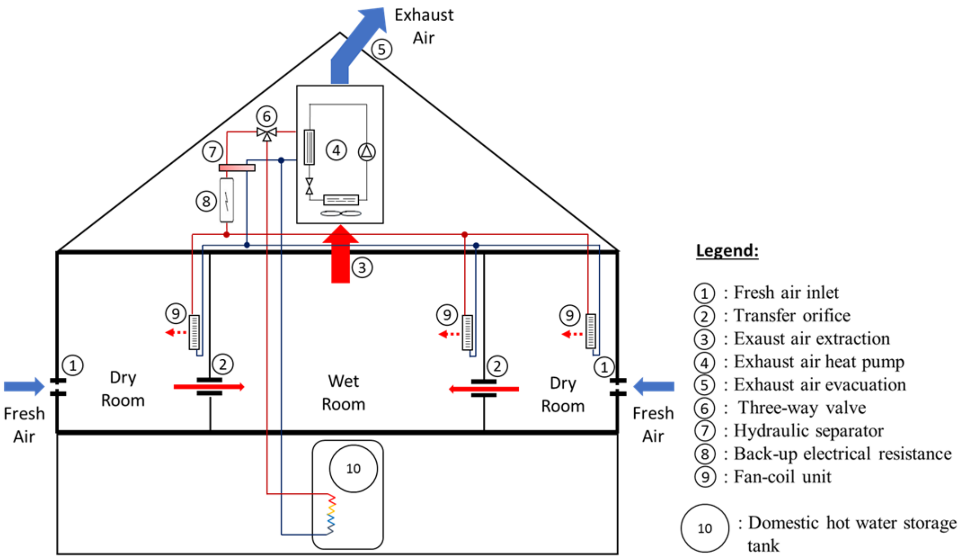


Figure 1: Simplified representation of the HVAC systems

The system consists of a simple exhaust ventilation system combined with a mini exhaust air heat pump used to heat the building and to produce the domestic hot water (4).

The fresh air from the outside environment enters the building through fresh air openings in the facade (1) and is mixed with the indoor air in the building dry areas. The air is moved from the dry to the wet areas by flowing through transfer orifices (2). The exhaust air, polluted with water vapor, CO_2 and other contaminants, is then extracted from the wet areas by using an axial fan (3). The fan operates continuously, regardless of the building occupancy. Thus, the ventilation air flow rate and the fan electrical consumption are constant and respectively equals 200 m^3/h and 55 W. After having been extracted, the exhaust air passes through a mini exhaust air heat pump (4) and is then evacuated (5).

The mini exhaust air heat pump (4) is an air-to-water heat pump characterized by an ultra-low heating capacity. In fact, in order to avoid the frost formation on the evaporator, the heating capacity is limited to 1400 W in nominal conditions. The refrigerant thermodynamic cycle includes a condenser, an evaporator, a rolling piston compressor and a thermostatic expansion valve.

The heat pump produces hot water that can be either used for the domestic hot water production or for the space heating. The hydraulic circuit connected to the heat pump consists of a three-way valve (6), a domestic hot water storage tank (10), a hydraulic separator (7), a backup electrical resistance (8) and fan-coil units (9) used to heat the building.

The three-way valve controls the heat pump operating mode. In fact, the machine can operate in “space heating mode” or in “domestic hot water production mode”.

In the “domestic hot water production mode”, the water temperature at the exhaust of the machine varies from 25°C (at the beginning of the domestic hot water production process) to 55°C (at the end of the domestic hot water production process). The thermal energy is stored in a 200-liter water storage tank situated in the garage. The domestic hot water set-point temperature is 50°C. In the actual control strategy, the domestic hot water production process starts at 11 PM and stops typically at 3 AM when the needs are satisfied.

In “space heating mode”, the water temperature at the exhaust of the machine is almost constant and varies from 40 to 45°C. A 3000 W backup electrical resistance in series with the machine can be switched on if the building heating demand is higher than the heat pump heating capacity. The terminal units consist of fan-coil units with a water temperature regime of 45/40°C.

3. DESCRIPTION OF THE SYSTEM INSTRUMENTATION

This section describes the different sensors placed in the building to measure the on-site performance of the heat pump. Figure 2 shows the position of the different sensors associated with the heat pump.
In order to measure the performance of the machine and the total electrical consumption of HVAC systems, the following sensors were installed in January 2017:

- Two temperature sensors at the supply and the exhaust of the heat pump, on the water side,
- Two temperature sensors at the supply and the exhaust of the back-up electrical resistance,
- One temperature sensor to measure the return temperature of the heating system,
- One water flow meter to measure the water volume flow rate at the supply of the machine,
- Three electric meters to measure the compressor consumption, the resistance consumption and the whole system consumption (compressor, resistance and auxiliaries), respectively.
- The weather conditions (temperature, humidity, wind and solar radiation) are retrieved by a weather station connected to the website WeatherUnderground. Its location is close to the house studied (less than 8 km).

Moreover, a sensor able to measure the mode ("DHW production mode" or "space heating mode") of the three-way valve was installed in April 2017. Finally, other sensors, such as temperature and humidity sensors and room temperature sensors were installed in September 2017.

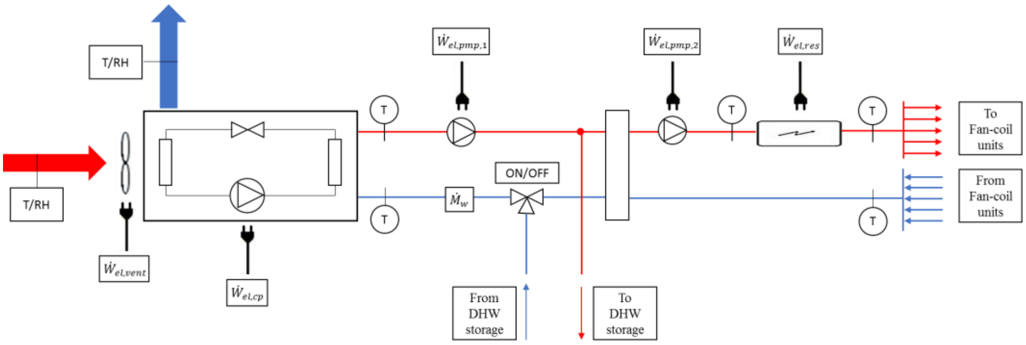


Figure 2: Position of the different sensors used to measure the on-site performance of the heat pump

The electrical power consumptions (resistance, compressor and the whole system) are measured by electronic devices (DRS155-D) with a resolution of 1 Wh. The air relative humidities and the air temperatures at the supply and at the exhaust of the heat pump are measured by digital sensors Telaire T9602. The other temperature sensors are digital temperature sensors DS18B20. They are directly put on the wall of the different parts of the heat pump with thermal pad and insulated, except one sensor that is let free in the ambient. Finally, a mechanical volume flow meter with Reed relay output is used to measure the water flow at the supply of the heat pump. It has a resolution of 0.25 liter per pulse. The accuracy of the different devices is listed in Table 3. The data acquisition system is built from a Raspberry Pi which is connected to all these sensors through python software. All the measurements are performed each minute.

Table 3: accuracy of the sensors placed in the building

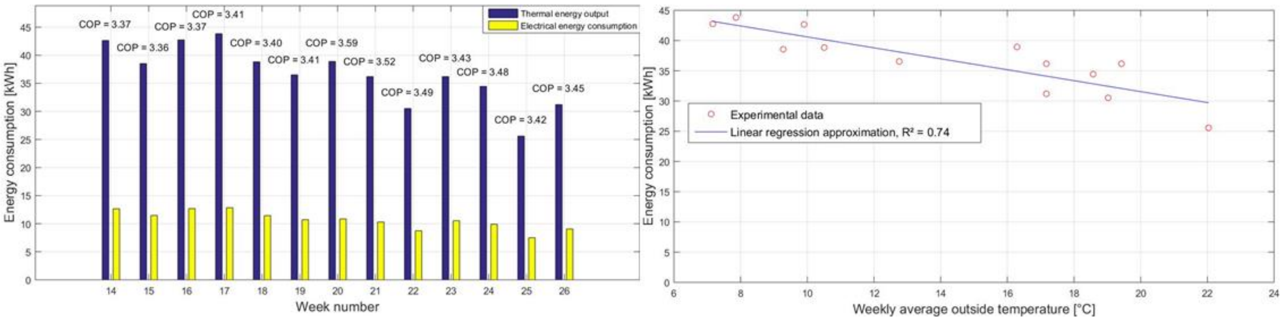
Measurement	Accuracy
Air humidity	±2 %
Air temperature (RH/T sensor)	±0.3 K
Other temperature	±0.5 K
Temperature difference	±0.2K
Water flow meter	±2 %
Power consumption meter	< 1 % (class 1)

4. ANALYSIS OF THE ON-SITE PERFORMANCE

This section presents and analyses the on-site performance of the machine. The results are presented from the 8th of January 2017 until the 2nd of July 2017, i.e from week 2 to week 26. The indoor temperature was not measured during this period, but the occupants did not complain about thermal comfort problems. Moreover, due to problems of communication with the unit, the performance for the weeks 3, 7, 8 and 13 are not available. For better readability, the results are presented on a weekly basis.

4.1 Performance in "Domestic hot water production mode"

Figure 3 shows the on-site performance of the heat pump in domestic hot water production mode. The left part of the figure (part (a)) represents the thermal energy output and the electrical energy consumption of the heat pump in kWh on a weekly basis. The weekly average COP (coefficient of performance) is also listed on the figure. The right part of the figure (part (b)) represents the thermal energy output of the heat pump in kWh as a function of the weekly average outside temperature.



(a) Thermal energy output and electrical energy consumption for the weeks 14 to 26

(b) Thermal energy output as a function of the weekly average outside temperature

Figure 3: On-site performance of the heat pump in domestic hot water production mode

The thermal energy output in DHW production mode varies from 44 to 25 kWh per week during the weeks 14 to 26 (see part (a) in Figure 3). This important variation is explained by a large range in the weekly outside temperature over the weeks, from 7 to 22°C. In fact, as shown in Figure 3 (part (b)), the thermal energy output of the heat pump in DHW production mode strongly depends on the outside temperature. The lower the outside temperature, the higher is the thermal energy output. A linear regression approximation (R^2=0.74) of the thermal energy output as a function of the weekly average outside temperature is given by Eq. 1:

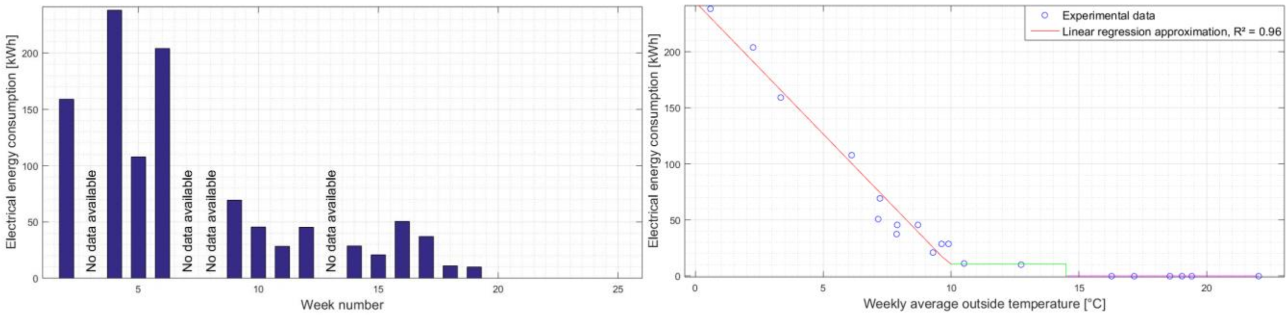
$$Q_{HP,DHW,week} = 49.65 - 0.9050\,.\,T_{out,avg,week} \quad (1)$$

where $Q_{HP,DHW,week}$ is the thermal energy output of the heat pump in DHW production mode in kWh on a weekly basis and $T_{out,avg,week}$ is the weekly average outside temperature in °C. This variation of the thermal energy demand related to the DHW production with the outside temperature is explained by three factors:

- The domestic hot water storage tank is situated in the garage, out of the building insulated shell. As a result, the thermal losses to the environment are higher in winter, because the outside temperature is lower.
- The mains water temperature at the supply of the storage tank decreases when the outside temperature decreases.
- The occupants' domestic hot water consumption may be higher in winter.

Contrary to the thermal energy output, the COP of the machine is relatively constant over the weeks. In fact, the COP varies from 3.36 to 3.59 (see part (a) in Figure 3), with an average value of 3.44. Indeed, the volume air flow rate, the supply air temperature and the water mass flow rate are almost constant, regardless of the value of the outside temperature. Moreover, regardless of the day considered, the temperature profiles (from 25°C to 55°C) during the domestic hot water production process are almost the same.

4.2 Consumption of the electrical resistance



(a) Electrical energy consumption of the backup electrical resistance for weeks 2 to 26

(b) Electrical energy consumption of the resistance as a function of the weekly average outside temperature

Figure 4: Energy consumption of the backup electrical resistance on a weekly basis

Figure 4 shows the energy consumption of the backup electrical resistance. The left part of the figure (part (a)) represents the electrical energy consumption of the backup resistance in kWh on a weekly basis. The right part of the figure (part (b)) represents the energy consumption of the backup resistance in kWh on a weekly basis as a function of the weekly average outside temperature.
The energy consumption of the backup electrical resistance varies from 240 to 0 kWh per week during weeks 2 to 26 (see part (a) in Figure 4). From week 2 to week 6, the consumption of the backup resistance is quite high, because the outside temperature is very low at that time of the year. From week 9 to week 19, the resistance consumption is lower because the outside temperature is higher at that time of the year. Finally, from week 20 to week 26, the electrical consumption drops to zero.
As shown in Figure 4 (part (b)), the energy consumption of the backup electrical resistance strongly depends on the outside temperature. Three different trends can be identified in Figure 4:

- If the weekly average outside temperature is lower than 10°C, the energy consumption of the backup resistance increases linearly when the outside temperature decreases. A linear regression approximation (R^2=0.96) of the energy consumption of the backup resistance as a function of the weekly average outside temperature is given by Eq. 2:

$$E_{el,res,week} = 244.3 - 23{,}54\ .\, T_{out,avg,week} \quad (2)$$

  where $E_{el,res,week}$ is the energy consumption of the backup resistance in kWh on a weekly basis and $T_{out,avg,week}$ is the weekly average outside temperature in °C.
- If the weekly average outside temperature is comprised between 10 and 14.5°C, the energy consumption is constant and equal to 10.5 kWh.
- If the weekly average outside temperature is higher than 14.5°C, the energy consumption is equal to 0 kWh.

4.3 Consumption of the whole system

Figure 5 represents the electrical energy consumption in kWh of the backup electrical resistance, the heat pump in heating mode, the heat pump in DHW production mode and the auxiliary equipment on a weekly basis.

In winter, when the weekly average outside temperature is lower than 7°C, the energy consumption of the resistance is higher than the energy consumption of the heat pump in heating mode. However, in mid-season, when the outside average temperature is comprised between 7°C and 14°C, the opposite phenomenon is observed.
As explained previously, the energy consumption of the heat pump in DHW production mode is a little bit more important in winter than in summer. Moreover, the energy consumption related to the auxiliary equipment is almost the same as the energy consumption of the heat pump in DHW production mode.

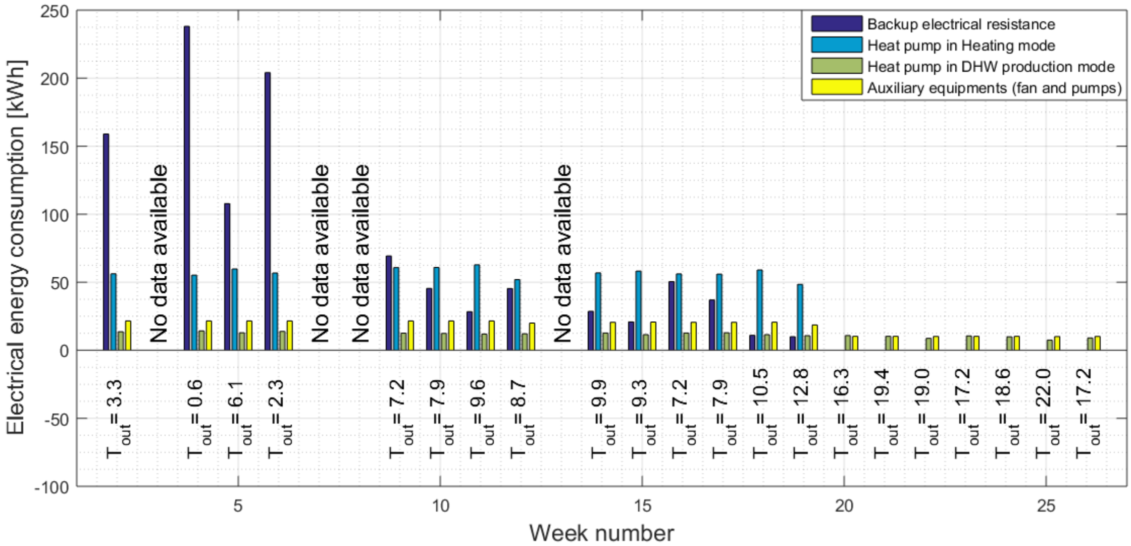


Figure 5: Electrical energy consumption of the backup electrical resistance, the heat pump in heating mode, the heat pump in DHW production mode and the auxiliary equipment on a weekly basis

4.4 Coverage rate

An important factor that must be determined is the coverage rate of the heat pump. This factor is defined as the thermal energy provided by the heat pump to the building divided by the total thermal energy demand of the building, as given by Eq. 3:

$$\tau = \frac{Q_{HP,DHW,week} + Q_{HP,Heating,week}}{Q_{HP,DHW,week} + Q_{HP,Heating,week} + E_{el,res,week}} \tag{3}$$

where τ is the coverage factor on a weekly basis, $Q_{HP,DHW,week}$ and $Q_{HP,Heating,week}$ are respectively the thermal energy output of the heat pump in DHW production mode and in space heating mode in kWh on a weekly basis and $E_{el,res,week}$ is the energy consumption of the backup resistance in kWh on a weekly basis.
As shown in Figure 6, the coverage factor depends on the outside temperature. As for the consumption of the electrical resistance, three different trends can be identified.

- If the weekly average outside temperature is lower than 10.5°C, the coverage factor decreases linearly when the outside temperature decreases. A linear regression approximation (R^2=0.97) of the coverage factor as a function of the weekly average outside temperature is given by Eq. 4:

$$\tau = 0{,}4 + 0.0467 \,.\, T_{out,avg,week} \tag{4}$$

  where τ is the coverage factor on a weekly basis and $T_{out,avg,week}$ is the weekly average outside temperature in °C. In that case, the coverage factor is lower than 1 because the heating capacity of the heat pump is not sufficient, compared to the total building heating demand. Consequently, the backup electrical resistance is activated.

- If the weekly average outside temperature is comprised between 10 and 14.5°C, the coverage factor is equal to 0.95. In that case, the heating capacity of the heat pump is sufficient to cover the building heating demand, but a low energy consumption of the resistance can occur during the night, when the heat pump operates in DHW production mode.
- If the weekly average outside temperature is higher than 14.5°C, the coverage factor is equal to 1. In fact, in that case, the heat pump provides all the energy demand related to the domestic hot water production and the building heating demand is null.

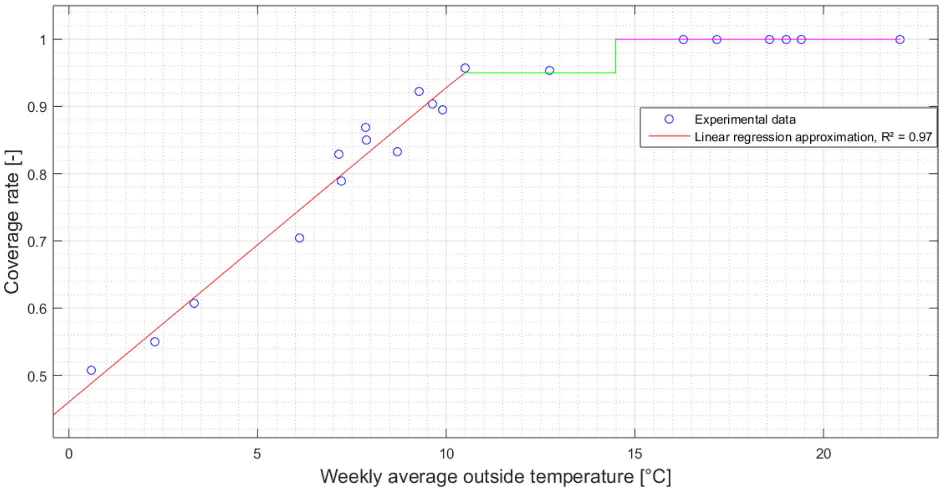


Figure 6: Coverage factor of the heat pump as a function of the weekly average outside temperature

6. CONCLUSIONS

The on-site performance of a mini-exhaust air heat pump integrated into a low energy detached house situated in Belgium have been presented and analyzed. The results show good performance of the exhaust air heat pump. In fact, the average COP of the machine in space heating mode and in DHW production mode are equal to 3.55 and 3.44, respectively. However, due to the limited heating capacity of 1400 W, the heat pump is not able to provide all the energy demand of the building, particularly in winter. Consequently, the electrical backup resistance is activated and the whole system efficiency decreases. A simple annual extrapolation of the results shows an annual coverage factor of 68 % and a seasonal COP of 1.95. A solution to increase the seasonal performance of the whole system would be an increase of the heating capacity of the machine, but it would create defrost losses. A better regulation of the ventilation and the heating systems would also decrease the annual consumption of the system. In fact, the use of a demand-driven ventilation system would decrease the consumption of the building. Moreover, the performance of the whole system depends on the insulation level and on the type of building. Future simulations will show the impact of the different solutions proposed.

REFERENCES

[1] European Commission, "DIRECTIVE 2010/31/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 May 2010 on the energy performance of buildings (recast)", *Official Journal of the European Union*, L 153/13 (2010). **E-Journal**

[2] European Commission, "DIRECTIVE 2012/27/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC", *Official Journal of the European Union*, L 315/1 (2012). **E-Journal**

[3] Liddament M.W., Orme M. "Energy and ventilation", *Applied Thermal Engineering*,18, pp 1101-1109 (1998). **Journal Paper**

[4] Orme M. "Estimates of the energy impact of ventilation and associated financial expenditures" *Energy and Buildings*, 33, pp 199-205 (2001). **Journal Paper**

[5] Moniteur belge. "Méthode PER – méthode de détermination du niveau de consommation d'énergie primaire des unités résidentielles". Retrieved February 15, 2018, from https://energie.wallonie.be/fr/exigences-peb-du-1er-janvier-2018-au-31-decembre-2020.html?IDD=114085&IDC=7224. (2017). **Web document**