PERFORMANCE MONITORING OF A HIGH-TEMPERATURE AIR-TO-WATER HEAT PUMP WITH INJECTION CYCLE INSTALLED IN A LOW-INSULATED SINGLE-FAMILY HOUSE IN BELGIUM

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Abstract: This paper deals with the performance monitoring and analysis of a capacity controlled high-temperature air-to-water heat pump with injection cycle. The heat pump has been installed in a low-insulated house in Belgium in March 2010 and is used for space heating in combination with panel radiators or for domestic hot water production. Firstly, we present the behavior of the heat pump in space heating mode as well as in domestic hot water production mode. Secondly, the influence of the injection and of the type of heaters on the performance of the heat pump in space heating mode is presented. Finally, the first results for seasonal performance are presented. These results show that the machine has an efficient control: injection starts for outdoor temperature where it is more efficient than the non injection cycle, defrosting periods are short due to the good management of the speed of the compressor and of the fan of the evaporator. This good behavior allows the heat pump to significantly increase the COP values compared to common air-to-water heat pumps.

Key Words: air-to-water heat pump, injection cycle, high-temperature, monitoring

1 INTRODUCTION

Heat pumps are nowadays world-wide recognized as efficient renewable energy systems for space heating and/or domestic hot water production from the viewpoint of primary energy consumption and CO_2 emissions. This efficiency depends on the SPF value which must be higher than 2.88 for the heat pump to be considered as a renewable energy system, as explained in (Dumont et al. 2011). A SPF higher than 2.88 is easy to obtain nowadays for heat pumps coupled to low-temperature heating systems like heating floors, what is usually not possible for ancient or renovated houses (Dumont et al. 2005a and 2005b, Dumont et al. 2007, Dumont et al. 2008a and 2008b, Duprez et al. 2008). The availability of high-SPF heat pumps in old or renovated ancient building stock, usually furbished with high-temperature heating systems (radiators), is then of high concern. In order to exhibit a high COP and a high heating capacity, more efficient heat pumps have been developed, which use the so-called injection cycle in combination with efficient control like a variable speed compressor. The purpose of this study is to monitor and analyze the performance of such a heat pump installed in a low-insulated house, firstly to determine its real SPF, and secondly to investigate the possibility of improvements. This paper presents the first experimental results.

2 SYSTEM DESCRIPTION AND MONITORING

2.1 System description

The dwelling is located near the city of Charleroi (Wallonia, south of Belgium) and is a four sides, single-family house, built in 1995. The heating system is composed of 11 radiators (8 at the basement, 3 at the first floor) which have been replaced in May 2010 by convector heaters. Details are given in (Dumont et al. 2011). The heat pump installed in the house is a

high-temperature air-to-water heat pump. It uses R410A as refrigerant in an injection cycle with internal heat exchanger (IHX) and a variable speed compressor control. It is used for space heating or domestic hot water (DHW) production. A tree-way valve sends the hot water either to the radiators or to a coil placed into a hot water tank. The heat pump design is sketched in figure 1.

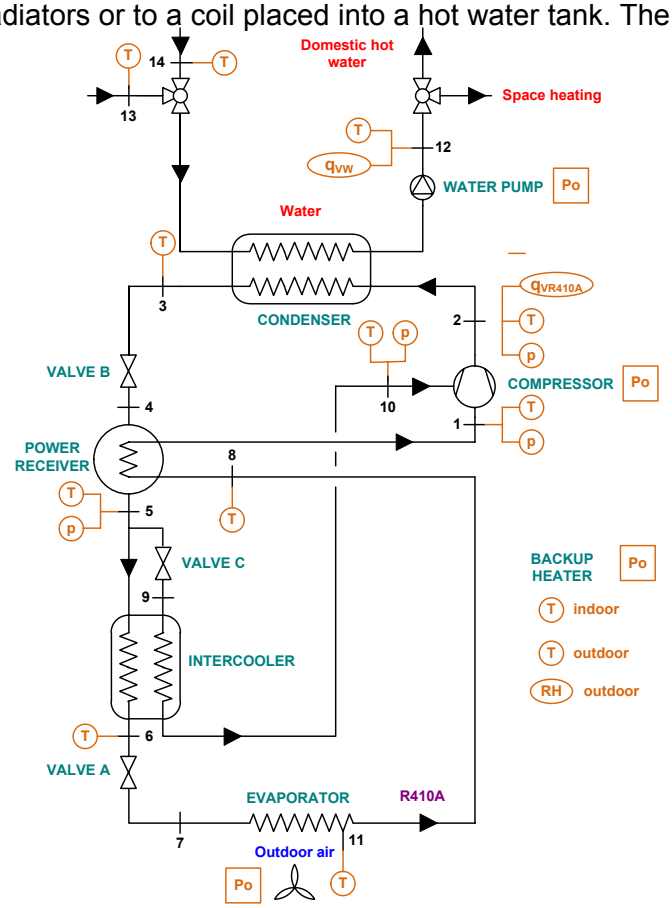


Figure 1: Heat pump configuration and sensors position for monitoring

The machine is composed of a scroll compressor, a plate condenser, an IHX (power receiver), an intercooler heat exchanger and a finned tubes evaporator (figure 1).
In non injection mode, R410A vapor at low pressure is superheated (8-1), compressed (1-2), condensed (2-3), expanded (3-4), condensed (4-5), expanded (6-7) and evaporated (7-8). In injection mode, operations (8-1), (1-2), (2-3), (3-4), (4-5), (6-7) and (7-8) remain the same. The major part of the liquid at point 5 is subcooled (5-6) in an intercooler while a small part of the liquid is expanded (5-9) and evaporated in the intercooler (9-10), then injected in the scroll compressor at point 10.

2.2 System monitoring

In order to achieve the heat pump measurements, the system has been equipped with sensors which measure temperatures (T), pressures (p), volume flow rates (q_{VR410A}, q_{VW}) and electric power of the outdoor unit (compressor and evaporator fan), of the circulation pump and of the back-up heater (Po). Evaporator surface temperature, indoor temperature, outdoor temperature and humidity (RH) are also monitored (figure 1). Each value is measured every second, averaged over one minute and stored in a data logger, then uploaded every week on a remote computer. Integration of the minute-average values gives daily values, monthly values then annual values. Table 1 presents the different sensors.
The measurement of temperature and pressure at the same point of the machine allows us to calculate thermodynamic properties like density ρ and specific enthalpy h. These properties lead to the determination of mass flow rates for R410A and water and then to the heat flow rate at the condenser, computed twice: by energy balance on R410A (2-3) and on

water (12-13). Calculation methods are given in (Duprez et al. 2008). The monitoring started in March 2010 and the results presented here stop on December 31st 2010.

Table 1: Sensors used for monitoring

Device	Range	Measurement point
Capacity pressure transducer	0-40 bar	1, 2, 5, 10
RTD (Class A) temperature sensor	-100-600°C	1, 2, 3, 5, 6, 8, 10, 11, 12, 13, 14
RTD (Class A) temperature sensor	-50-50°C	Indoor, outdoor
Capacity relative humidity sensor	0-100 %	Outdoor
Vortex volume flow meter (R410A)	0-2 dm^3/s	2
Electromagnetic volume flow meter (water)	0-0.88 dm^3/s	12
Power analyzer	0-9 kW	Outdoor unit, backup heater,
Power analyzer	0-200 W	Water pump

3 RESULTS

3.1 Space heating

3.1.1 Daily values – autumn

The results presented in figure 2 were recorded on November 19th 2010 and are typical of a mild weather (autumn-spring).
For this day, the outdoor temperature is about 9°C. There are 5 main heating cycles in which cycle #4 is composed of 13 small heating cycles. Each main cycle begins with a heat flow rate peak which decreases after 15 min and remains constant until the end of the cycle. This decrease seems to limit the condensation temperature at about 42-45°C while the evaporation temperature increases from about 0 to 5°C. The indoor temperature increases from 19 to 22°C. The variation of the outdoor unit electric power is similar to the variation of the heat flow rate. The water pump only circulates water during a heating cycle. The COP is high at the beginning of the cycle because the water coming from the radiator is cold. The COP decreases during the heating up of the water due to the thermal inertia of the water and the radiators (15 first minutes of a heating cycle). The COP then increases due to the increase of the evaporation temperature at quasi-constant condensation temperature. The results show the advantage of the speed control of the compressor/evaporator fan to obtain high COP and long cycles even at mild outdoor temperatures. The heat pump runs the whole day without injection, without defrosting and without backup heater.

3.1.2 Daily values - winter

The results presented in figure 3 were recorded on December 2nd 2010 and are typical of a cold winter day.
For this day, the outdoor temperature is about -3.5°C. There are 4 main heating cycles interrupted by short defrosting cycles. Each main cycle exhibits the same behavior as the cycles of November 19th. Several differences are however pointed out. Here, the heat pump works nearly always with injection except for the third cycle around 12:00. Injection seems to be used to reach a condensation temperature of about 50°C needed by the low outdoor temperature (-5°C during the morning). Injection is stopped at noon when the outdoor temperature is about -1°C and a condensation temperature of about 45°C is enough to keep comfortable indoor temperature (like on November 19th). Evaporation temperature is around -10°C and exhibits quick falls due to frost. Defrosting seems efficient since it only occurs 11 times in a day (total of 32 min within 959 min uptime, i.e. 3.3%). COP values are rather good because of the efficient control of the outdoor unit speed. They exhibits small falls before defrosting cycles.

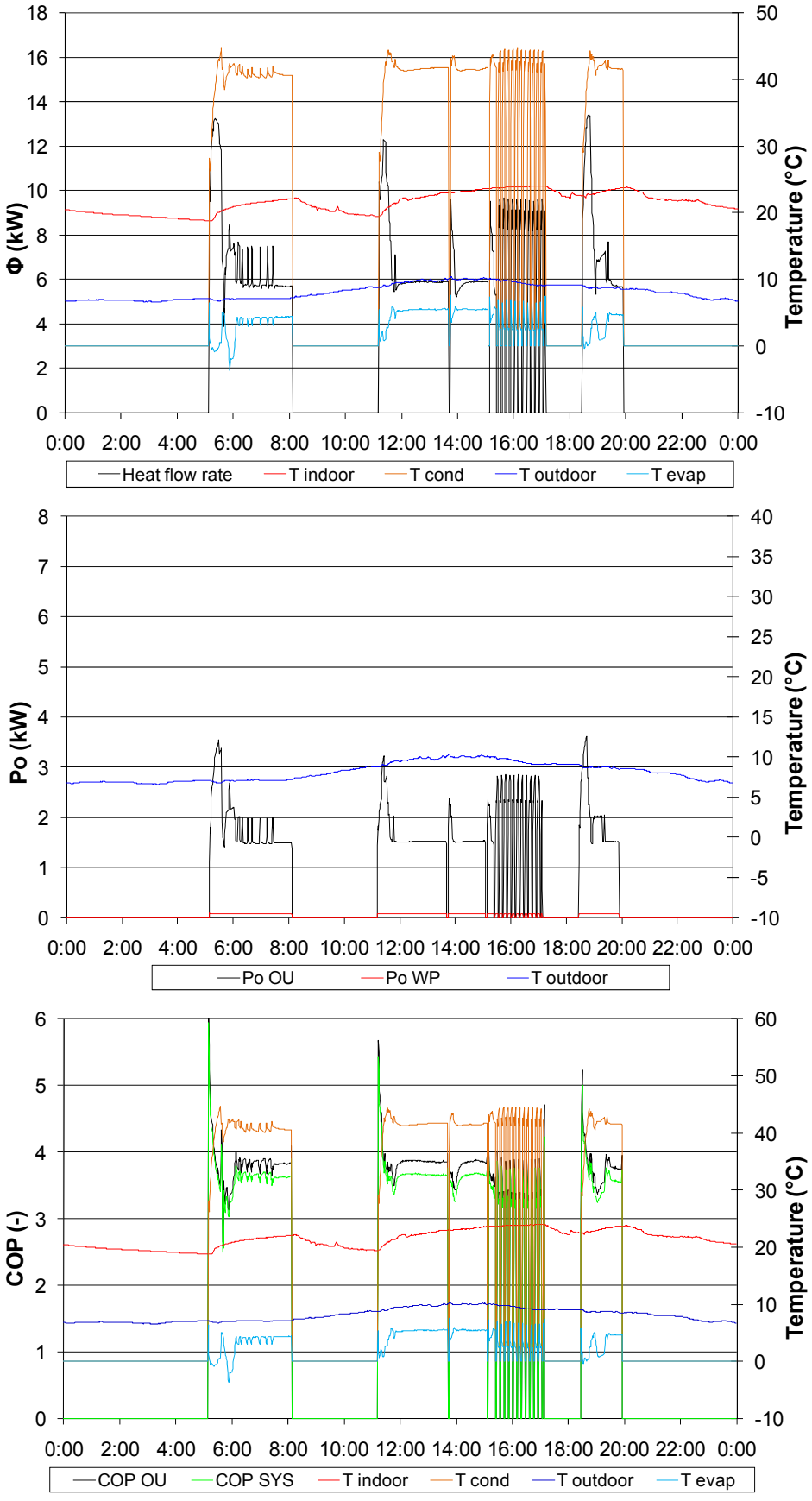


Figure 2: Condenser heat flow rate ϕ (top), electric powers Po (middle) and COP (bottom) for November 19th 2010

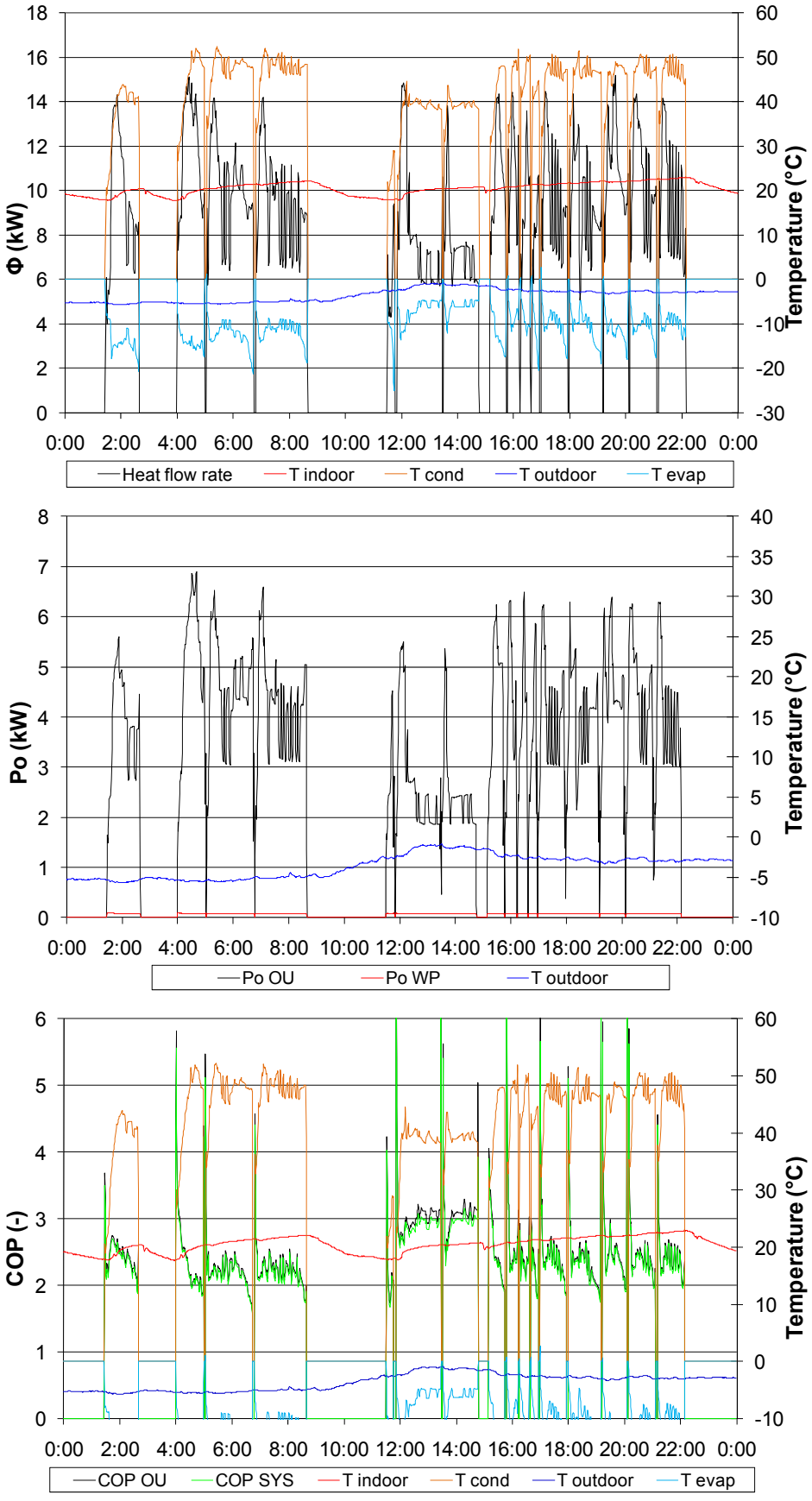
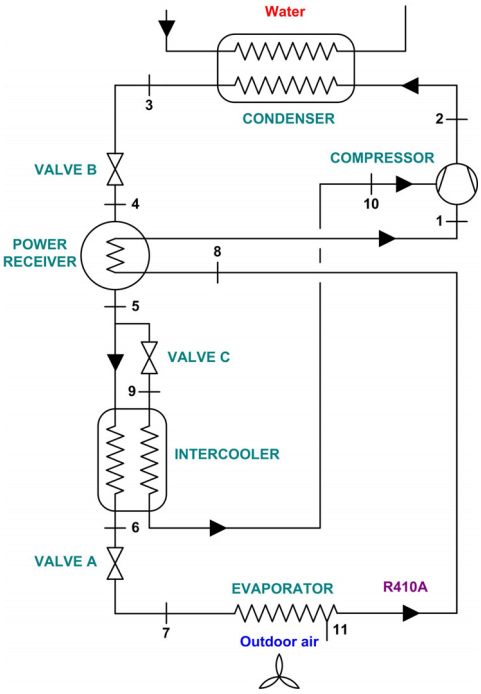


Figure 3: Condenser heat flow rate ϕ (top), electric powers Po (middle) and COP (bottom) for December 2nd 2010

3.1.3 Injection analysis

From the recorded values, it seems that injection can only occur when $T_{OUTDOOR}$<5°C. This criterion is not sufficient and a second criterion related to the temperature of the gas at the compressor outlet seems to be used.
Figure 4 presents the measured thermodynamic cycle without or with injection. It shows that injection of cold gas in the compressor at a pressure between the suction and the exhaust pressures allows the system to reduce the temperature of the refrigerant at the outlet of the compressor.



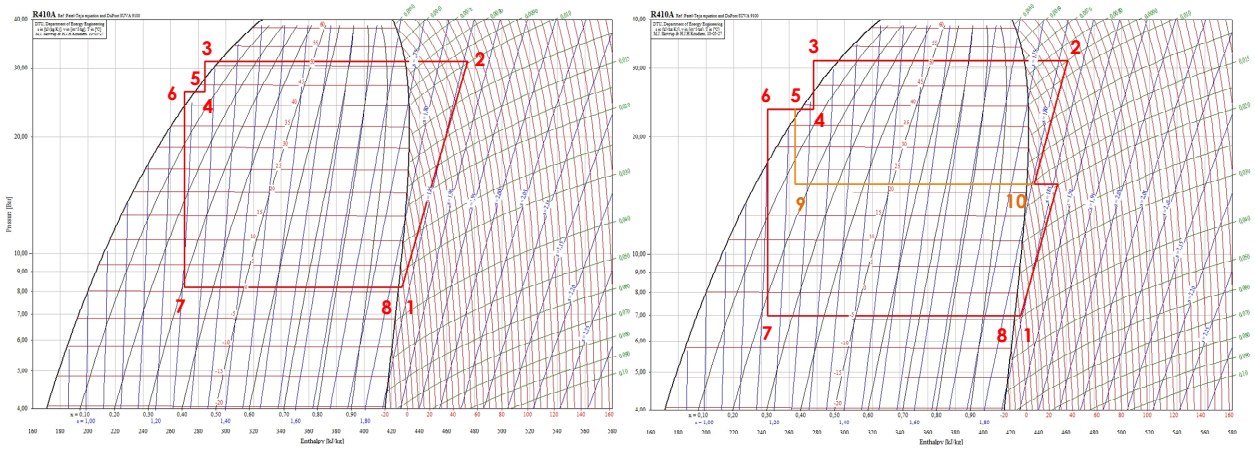


Figure 4: Heat pump cycle without (left) and with injection (right) (experimental data)

The main reason for the use of an injection cycle is to boost the heat flow rate delivered by the heat pump. In order to be efficient, this boost must not lead to a decrease of the COP. In order to validate these assumptions, the heat flow rate ϕ and the COP with and without injection are presented in figures 5 and 6, respectively (each point is an average measurement over one minute).

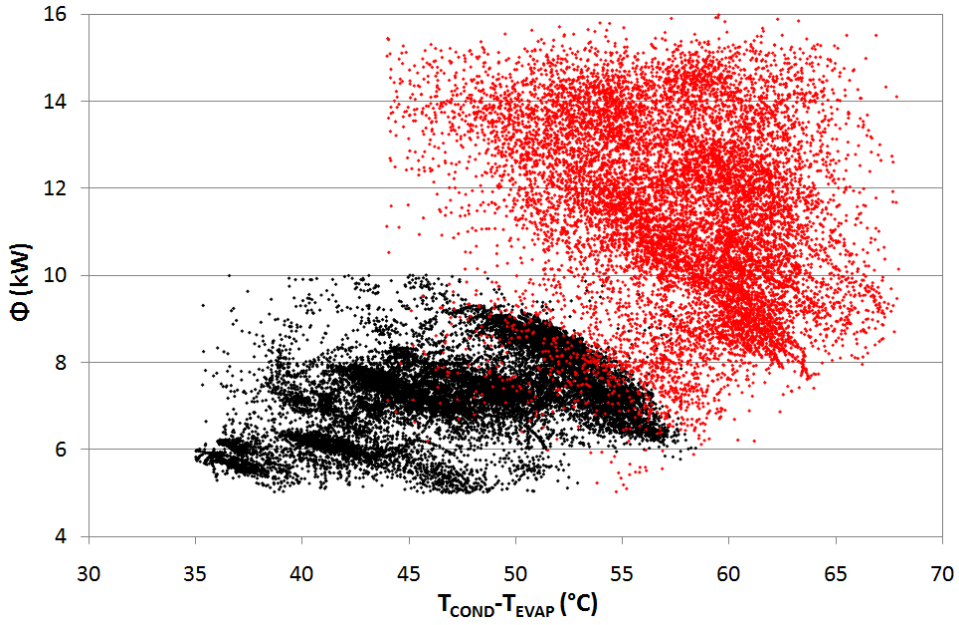


Figure 5: Condenser heat flow rate Φ versus T_{COND}-T_{EVAP} with (♦) or without injection (♦)

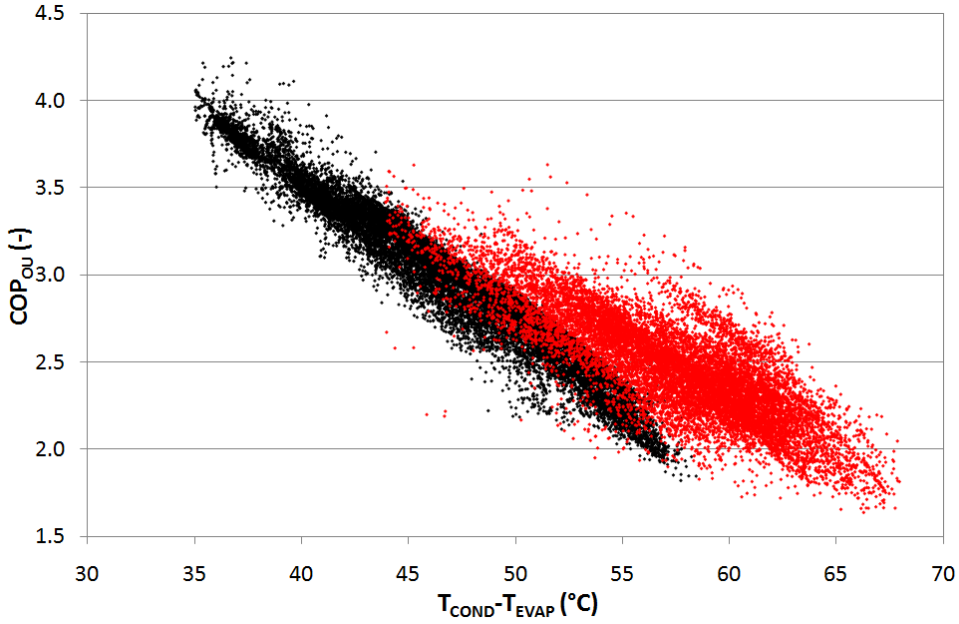


Figure 6: COP_{OU} versus T_{COND}-T_{EVAP} with (♦) or without injection (♦)

Figure 5 shows that when injection occurs, the heat flow rate increases dramatically: it is limited to 10 kW without injection but can reach 16 kW with injection. Figure 6 shows that the injection is efficient because the COP keeps values of about 2.0 when injection is used what will not be the case if the injection is not used. These two figures lead to conclude that the injection process is efficient and well controlled.

3.1.4 Radiators versus convector heaters

As mentioned above, the radiators which were used with the gas boiler in the house were replaced by convector heaters mid-May 2010. Figure 7 compares the monitored daily performance of the heat pump before (radiators) and after the change (convector heaters).

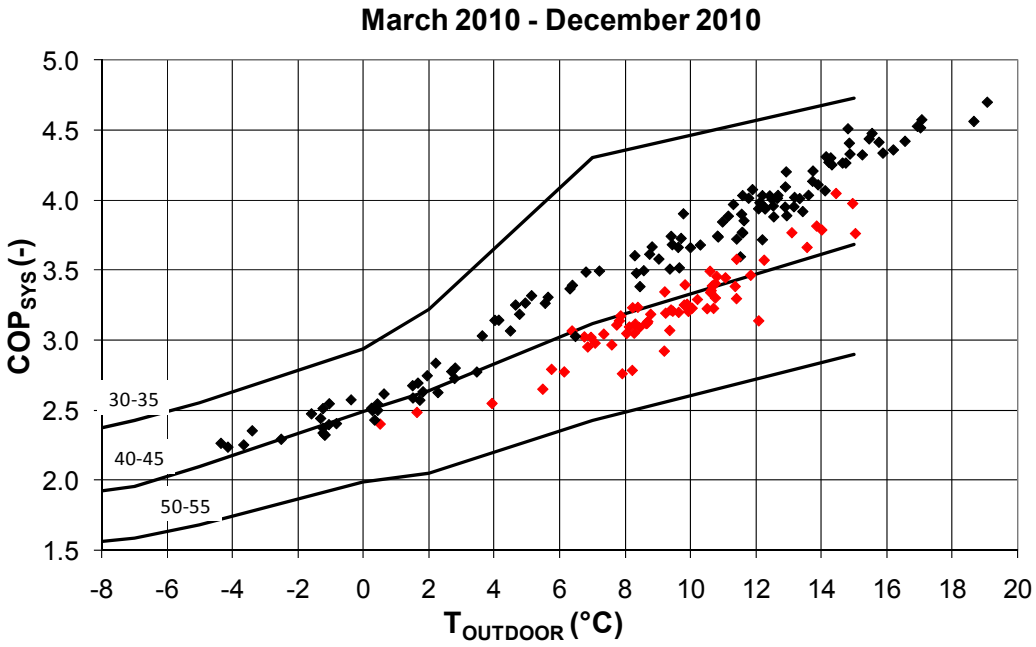


Figure 7: Daily COP_{SYS} versus $T_{OUTDOOR}$ for heat pump with convector heaters (♦) or radiators (♦). The curves are manufacturer data for different water regimes

Figure 7 shows an increase of COP of about 0.3 due to the change of the radiators. For mild weather conditions, radiators used a 40-45°C water regime while convector heaters use a lower regime (35-40°C). For winter weather conditions, the convector heaters run with a 40-45°C water regime. The few measurement points for low outdoor temperature with radiators exhibit what looks like a strange behavior: the water regime seems to remain 40-45°C. This oddity is due to the heat pump control which stopped the heating cycle when water was higher than 45°C. Figure 7 shows also a good agreement with the manufacturer data trends.

3.2 Domestic hot water production

DHW is produced by the same heat pump as the one used for space heating. Both heating modes cannot occur simultaneously. DHW is usually produced at fixed periods of time during the night, and has priority to space heating. The instantaneous behavior is similar to what has been presented for space heating in §3.1.1 and 3.1.2. The use of injection is similar to what is observed in space heating mode. Figure 8 presents the daily performance of the heat pump for DHW production.

Contrary to space heating, DHW is produced over the whole year, i.e. also during summertime. As the outdoor temperature can reach high value during the summer, the COP should also be high. Figure 8 shows that the increase of COP tends to be limited for high outdoor temperatures. This can be explained by the fact that the heat flow rate ϕ delivered to the water tank is higher for high outdoor temperature (high evaporation temperature), with a quasi-constant condensation temperature. As the evaporator has a fixed UA value, the evaporator LMTD increases and the trend in COP increase is flattened. The evaporator LMTD versus $T_{OUTDOOR}$ is presented in figure 9. The heat pump control strategy is not known but it is assumed that it decreases the compressor speed in order to keep the evaporator LMTD constant for $T_{OUTDOOR}$ ranging from -6°C to about 15°C. When the minimum available speed is reached, the evaporator LMTD increases ($T_{OUTDOOR}$ higher than 15°C).

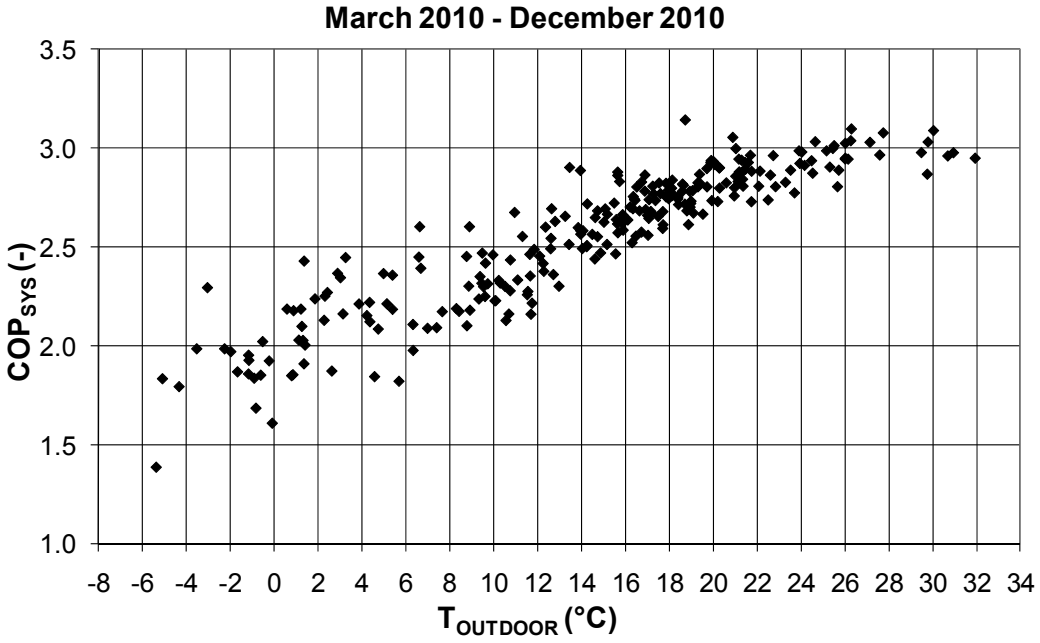


Figure 8: Daily COP_{SYS} versus $T_{OUTDOOR}$ for heat pump in DHW production mode

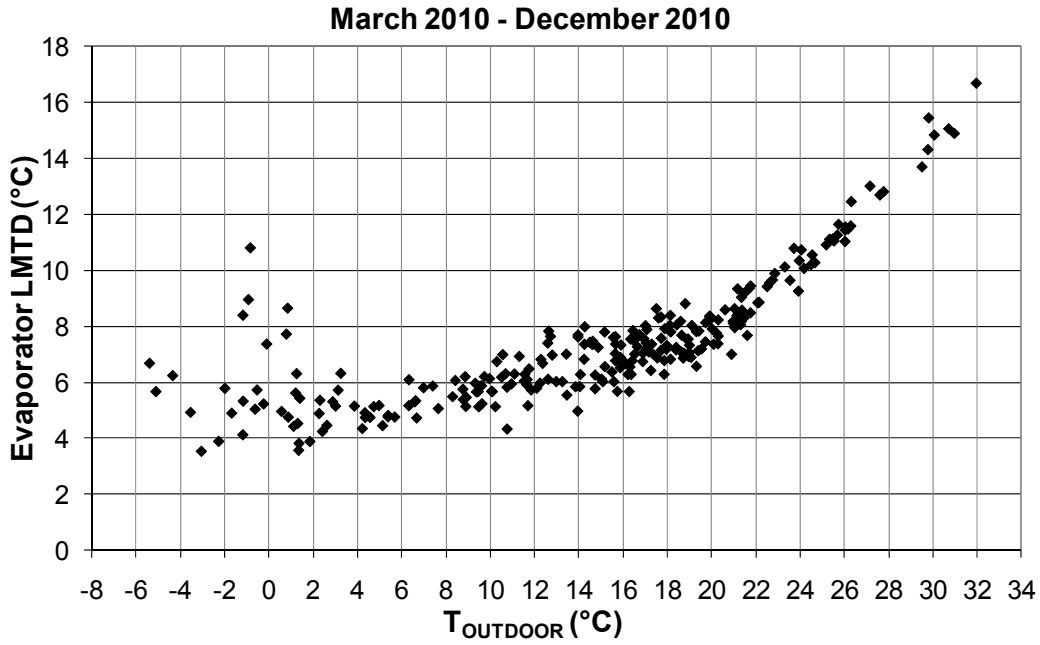


Figure 9: Daily average evaporator LMTD versus $T_{OUTDOOR}$ in DHW production mode

3.3 Seasonal performance

Month performances values for space heating (from March 10th 2010 to December 31st 2010) are presented in Table 2 where several energy consumption values are presented: E_{OU} (outdoor unit, i.e. compressor and evaporator fan), E_{WP} (condenser water pump), E_{CH} (fans of the convector heaters), E_{BH} (electric backup heater) and E_{SB} (heat pump stand-by energy, that is control electronic and carter resistor consumption). Q is the heat delivered to the water circulating in the radiators. $COPM_{OU}$ includes only E_{OU} while $COPM_{TOT}$ includes all kinds of energy consumption. We assumed that the stand-by energy is to be included in space heating calculation and not in DHW production. Let's note that the values for March, October

and November do not reflect a whole month monitoring (recording began on March 10th and the heat pump was in stand-by for maintenance from October 19th to November 8th).

Table 2: Month performance for space heating

Month	E_{OU} (kWh)	E_{WP} (kWh)	E_{CH} (kWh)	E_{BH} (kWh)	E_{SB} (kWh)	Q (kWh)	$COPM_{OU}$ (-)	$COPM_{TOT}$ (-)
March	498.31	14.34	0.12	0.00	14.27	1466.82	3.00	2.83
April	415.05	14.13	0.38	0.00	19.85	1356.28	3.27	3.02
May	263.90	9.44	1.07	0.00	22.46	903.23	3.42	3.04
June	28.67	1.32	0.63	0.00	24.04	120.63	4.21	2.21
July	0	0	0	0.00	22.19	0.00		
August	9.33	0.52	0.25	0.00	24.97	41.93	4.50	1.20
September	76.07	3.56	1.73	0.00	24.76	319.57	4.20	3.01
October	130.39	5.32	2.57	0.00	13.30	508.34	3.90	3.35
November	548.00	17.05	8.28	0.77	10.46	1703.29	3.11	2.92
December	1505.29	36.06	17.42	1.25	9.30	3899.20	2.59	2.49

Table 2 shows that E_{OU}, E_{WP} and Q exhibit an usual profile over the months (high values during winter and low values during summer). E_{CH} is low for March and April because the convector heaters were placed only mid-May 2010. E_{BH} is nearly zero because the injection process is able to deliver the required heat even for low outdoor temperatures (figure 5).
E_{SB} is quite constant and higher during summer due to the low uptime of the heat pump. $COPM_{OU}$ values are higher in summer due to high evaporation temperatures. $COPM_{TOT}$ is low during summer due to the integration of E_{SB} in the calculation.
The values of E_{CH} for March and April are low because radiators were used (with only one convector heater) and were only replaced mid-May. It is estimated that if convector heaters have been used in March and April, the COPM values would have been 0.2 to 0.3 higher.
Month performances values for DHW production (from March 10th 2010 to December 31st 2010) are presented in Table 3. Here, there are no convector heaters or stand-by energy consumption. As mentioned above, $COPM_{OU}$ includes only E_{OU} while $COPM_{TOT}$ includes all kinds of energy consumption.

Table 3: Month performance for DHW production

Month	E_{OU} (kWh)	E_{WP} (kWh)	E_{BH} (kWh)	Q (kWh)	$COPM_{OU}$ (-)	$COPM_{TOT}$ (-)
March	63.63	1.88	0.00	149.79	2.35	2.29
April	78.11	2.50	0.00	202.57	2.59	2.51
May	79.86	2.52	0.00	204.76	2.56	2.49
June	74.31	2.29	0.00	218.15	2.94	2.85
July	64.36	1.94	0.00	190.83	2.96	2.88
August	48.56	1.53	0.00	142.81	2.94	2.85
September	68.15	2.23	0.00	192.73	2.83	2.74
October	40.81	1.31	0.00	110.37	2.70	2.62
November	47.04	1.26	0.00	111.68	2.37	2.31
December	89.99	2.23	0.00	183.09	2.03	1.99

Table 3 shows that E_{OU} exhibits a profile similar to the space heating profile while E_{WP} and Q exhibit a constant profile over the months (DHW production do not depend of the weather). E_{BH} is zero for the same reason as for space heating. COPM values are higher in summer than in winter for the same reasons as for space heating.

4 CONCLUSION

A high-temperature heat pump installed in a low-insulated single-family dwelling has been analyzed and its performance monitored since March 2010. The first results presented in this paper show that the use of the injection cycle for low outdoor temperature allow to deliver high heat flow rates while keeping interesting COP values. The efficiency of the injection cycle also allows the heat pump to deliver the required heat without use of the backup heater. The outdoor unit speed control allows the system to heat up the house with the lowest condensation temperature in order to have the best COP and to avoid short heating cycle behavior. The management of defrosting is also good. From the European regulation viewpoint, the target SPF (2.88) may be reached for the system investigated.

5 NOMENCLATURE

h	Specific enthalpy [kJ/kg]
p	Pressure [bar]
q_{VR410A}	R410A volume flow rate [dm^3/s]
q_{VW}	Water volume flow rate [dm^3/s]
COP	Coefficient of performance of a heat pump [-]
COP_{OU}	Coefficient of performance including only outdoor unit [-]
COP_{SYS}	Coefficient of performance including only outdoor unit and water pump [-]
$COPM_{OU}$	Month COP including only outdoor unit [-]
$COPM_{TOT}$	Month COP including all electric consumptions [-]
E_{BH}	Seasonal electric consumption of the backup heater [kWh]
E_{CH}	Seasonal electric consumption of the convector heaters [kWh]
E_{OU}	Seasonal electric consumption of the outdoor unit [kWh]
E_{SB}	Seasonal electric consumption during stand-by [kWh]
E_{WP}	Seasonal electric consumption of the condenser water pump [kWh]
LMTD	Log mean temperature difference [°C]
Po	Electric power [W]
Po_{OU}	Electric power of the outdoor unit [W]
Po_{WP}	Electric power of the condenser water pump [W]
Q	Seasonal heat delivered to the house [kWh]
RH	Relative humidity [%]
SPF	Seasonal performance factor of a heat pump [-]
T	Temperature [°C]
T_{COND}	Condensation temperature [°C]
T_{EVAP}	Evaporation temperature [°C]
T_{INDOOR}	Indoor temperature [°C]
$T_{OUTDOOR}$	Outdoor temperature [°C]
ρ	Density [kg/m^3]
ϕ	Condenser heat flow rate [W]

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