PERFORMANCE ANALYSIS OF HIGH-TEMPERATURE HEAT PUMPS INSTALLED IN LOW-INSULATED DWELLINGS: CASE OF A SINGLE-FAMILY HOUSE IN BELGIUM

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Abstract: This paper deals with the performance analysis of high-temperature heat pumps installed in renovated low-insulated dwellings. This analysis has been applied to a heat pump with injection cycle installed in a single-family house in Belgium. The thermal behavior of the house and the performance of the heat pump have been modeled in TRNSYS. Firstly, the model is used to estimate the performance of the installed system and secondly to perform a parametric study by testing heat pumps with different heating capacities, with and without injection cycle, by changing the insulation level of the house or by testing different types of radiators. The model gives a SPF=2.86 for the installed system and shows that the heat pump is a little oversized, that a reduction of energy consumption (14%) and an improvement of the SPF (up to 3.32) can be obtained by increasing the surface area of the radiators by 50% or by a better insulation of the house (20 cm mineral wool under the roof, 3 cm of expanded polystyrene under the floor, new double glazing windows).

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

1 INTRODUCTION

Heat pumps are nowadays world-wide recognized as efficient renewable energy systems for space heating, i.e. low CO_2 emission and low primary energy consumption. A recent European Directive (EP 2009) states that in order to be accounted in primary energy reduction goals, heat pump systems must use about 13% less primary energy than traditional systems. Most heat pumps are vapor compression systems which use electricity. As the average power plant primary energy efficiency chosen by the European Union is 40% (resulting from an average electricity mix of the European countries), that means that a SPF of about 2.88 must be reached to match the 13% primary energy reduction.
A SPF higher than 2.88 is easy to obtain nowadays for heat pumps coupled to low-temperature heating systems like heating floors (water circulating in the floor has usually a temperature of about 35°C). For air source heat pumps, the SPF can now reach 3.2 (Dumont et al. 2005, Dumont et al. 2007, Dumont et al. 2008a and 2008b, Duprez et al. 2008) and for vertical ground source heat pumps, it can be higher than 4.0 (Schiffman et al. 2009). Unfortunately, heating floors are usually installed in new buildings, not in ancient ones, due to the complexity and cost of replacement of an ancient massive floor by a new insulated one. As the percentage of new buildings in a country building stock is very low (20 % of buildings are less than 20 years old in Belgium (BFG 2005)), the introduction of high-SPF heat pumps in old or renovated building stock, usually furbished with high-temperature heating systems, is of high concern.
Simple vapor compression cycle heat pumps coupled with high-temperature heating systems like radiators or convection heaters cannot balance the high thermal losses of low-insulated dwellings for low, wintertime outdoor temperatures. Therefore, 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 paper is to investigate, through

simulation, the performance of such new heat pumps installed in low-insulated dwellings. We first model a real system installed in a single-family house in Belgium. Secondly, we perform a parametric analysis of the performance of the installed system by changing the heat pump itself, the radiators and the insulation level of the house.

2 SYSTEM DESCRIPTION AND MODELING

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 (figure 1). It has 3 floors: the underground floor (garage, cellar), the basement floor and the first floor (under the roof). Only a part of the underground floor is under the ground. The main façade is oriented west. The walls are insulated with 3 cm of expanded polystyrene and the roof with 12 cm of mineral wool. The total thermal losses surface area A_{TOT}=482 m^2 in which the windows surface area A_{WIN}=14 m^2. The average heat transfer coefficient U_{TOT}=1.0 W/(m^{2}K) and the windows heat transfer coefficient U_{WIN}=2.57 W/(m^{2}K).

Figure 1: House investigated

Before the installation of a heat pump in March 2010, the house was heated with a gas boiler. The heat pump installed in the house is a high-temperature air-to-water heat pump. It uses R410A in a so-called injection cycle with internal heat exchanger and a variable speed compressor control. The machine is described in detail in another paper (Dumont et al. 2011). The injection of cold gases in the compressor at a pressure between suction and exhaust pressures allows to reduce the temperature of the refrigerant at the outlet of the compressor, to increase the heat capacity of the heat pump and sometimes to increase its COP (Heo et al. 2010), allowing the heat pump to deliver high heat flow rates even at low outdoor temperature. The heating system is composed of 11 radiators (8 at the basement, 3 at the first floor).

2.2 System modeling

The system has been modeled in TRNSYS 16 (SEL 2004). This dynamic simulation environment needs at least 3 sub-models called 'types' connected with each other: one for the dynamic thermal behavior of the house, one for the heat pump and one for the radiators. Other sub-models are used for the weather data simulation and for the control of the on/off pattern of the heat pump (figure 2). The simulation integration step for the algebraic-differential equation set has been set to 5 min, in order to account for the dynamic behavior of the radiators.

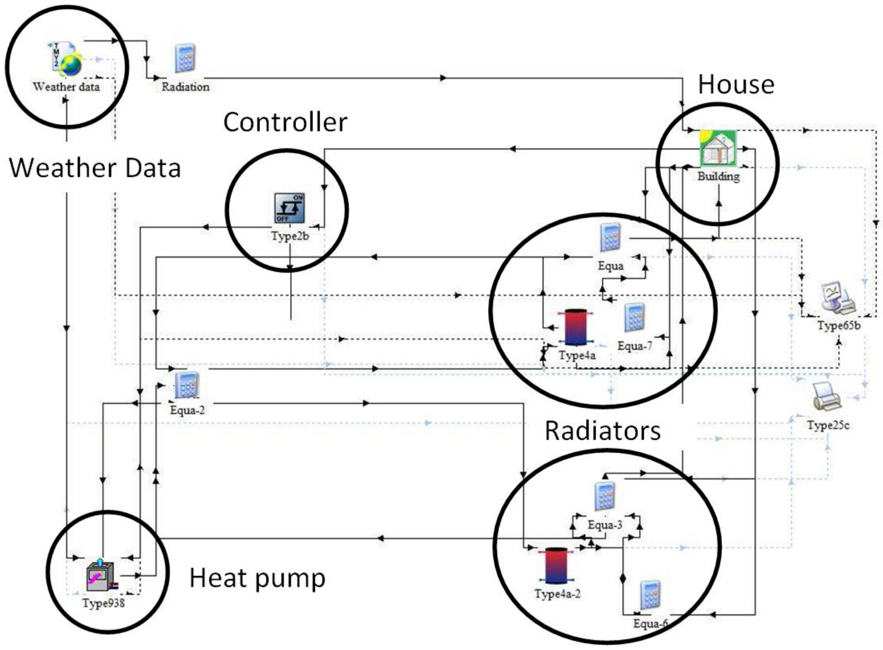

Figure 2: Model of the system in TRNSYS 16 environment

2.2.1 House modeling

The house has been modeled as a 'five zones' thermal model in type 56 of TRNSYS as labeled on figure 3. Each thermal zone has its own indoor air temperature, heating and cooling demands. Zones 1 (basement) and 2 (first floor) only are heated by the heat pump. The walls, roof and windows are defined according to their material composition and surface areas. No internal gains (presence of people or of equipments) are used in the model. An air infiltration rate of 1.0 h^{-1} is used in all zones. The solar gains and the outdoor temperature are read in standard files which contain hourly weather data for an average year in Uccle (Belgium).

TRNSYS calculates the annual heating and cooling demand of a building for a given indoor temperature profile or to inject or extract heat out of the building by using a controller. We used both methods; for the first one, we used a temperature profile defined as follows: T_{INDOOR}=22°C during the day and T_{INDOOR}=18°C during the night for the basement, and T_{INDOOR}=18°C for the first floor. For the second method, the controller (type 2) sets the heat pump on when T_{INDOOR} in the basement is lower than 18°C and stops the heat pump when this temperature reaches 20°C.

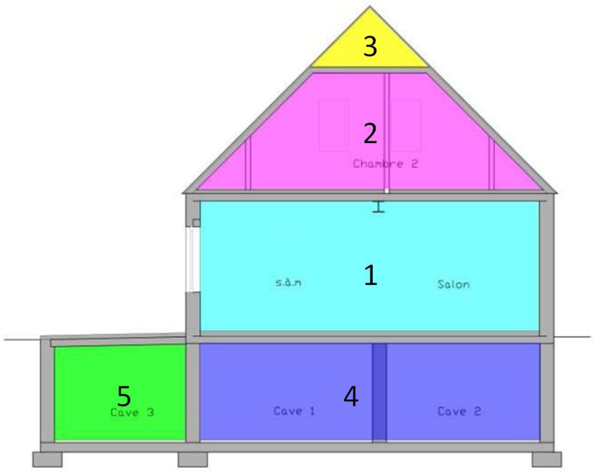

Figure 3: The five thermal zones of the house

2.2.2 Heat pump modeling

In TRNSYS, all the heat pump models are static models, meaning that the heat pump quickly reaches a steady state in comparison with the dynamic behavior of the house. This means that we do not use a 'short cycle' penalty factor in the model (Bettanini et al. 2003). The steady-state performance is given in a two-dimension table (condenser heat flow rate and heat pump electric consumption versus outdoor temperature and water temperature at the condenser inlet) which contains data from the heat pump manufacturer. The heat pump model used has been type 938 from TESS.

2.2.3 Radiators modeling

There is no radiator model in the TRNSYS libraries so we have created our own model by defining thermal equations in TRNSYS. We model the 8 radiators of the basement (zone1) as a single radiator and the 3 radiators of the first floor (zone 2) as another single radiator. We express the heat balance in a single radiator as follows:

$$\phi_{RAD}=UA\,((T_{WIN}+T_{WOUT})/2-T_{INDOOR}) \qquad (1)$$

$$\phi_{RAD}=q_{MW}\,c_{PW}\,(T_{WIN}-T_{WOUT}) \qquad (2)$$

That means that we can compute the heat flow rate released by the radiator ϕ_{RAD} and the water outlet temperature T_{WOUT} in function of inlet water temperature T_{WIN} (coming from the heat pump) and of indoor air temperature T_{INDOOR}.
The heat transfer rate U has been fitted (polynomial fit) with radiator manufacturer data in function of T_{WIN} and then multiplied by the total surface area A of all the radiators of a zone:

$$UA=a_R T^2_{WIN} + b_R\,T_{WIN} + c_R \qquad (3)$$

In order to account for the thermal inertia of the radiators, we used a capacity model (perfectly mixed water tank) whose water mass m_W is equal to the water content of all radiators in a zone (type 4a). This capacity model was placed in series after the radiator equations and gives the tank water outlet temperature T_{WOUT2} which is the temperature of the water going back to the condenser of the heat pump:

$$q_{MW}\,c_{PW}\,(T_{WOUT2}-T_{WOUT})=m_W\,c_{PW}\,dT_{WOUT2}/dt \qquad (4)$$

3 RESULTS

The system model has been used to simulate the heat demand of the house and the installed heat pump performance for a whole year (SPF, power consumption). Then, some parametric studies have been conducted to evaluate the sensitivity of the heat pump performance to several changes in the original configuration.

3.1 Performance of the installed system

3.1.1 Dwelling heat demand

In order to validate the thermal model of the house, we first calculate the heat demand of the house with the indoor temperature profiles defined in §2.2.1 (figure 4). The simulated annual heat demand is 27407 kWh which is similar to the real heat demand determined from gas provider bills for 3 years (between 23375 and 28943 kWh).The cooling demand has also been evaluated for first floor temperatures higher than 24°C: this temperature is only higher during 18 hours in a year so that the cooling demand can be assumed equal to zero.

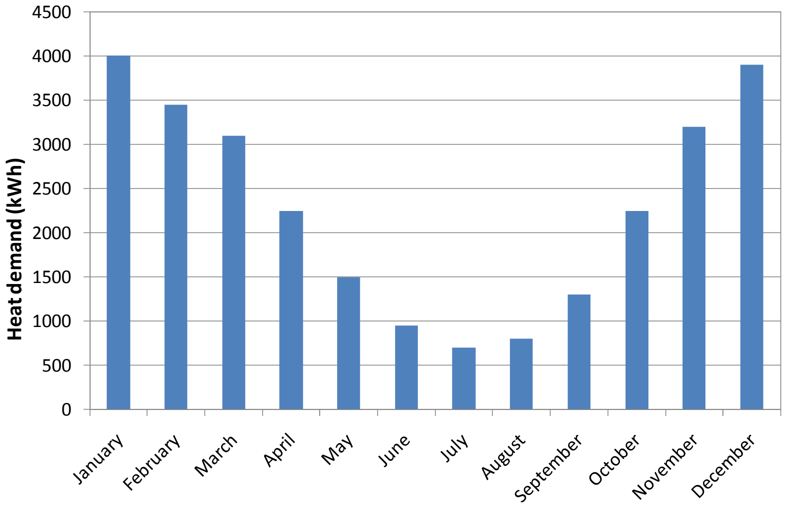

Figure 4: Simulated monthly heat demand of the house

The instantaneous heat flow rate (ϕ_{HO}) needed by the house is also available. We can therefore determine the heat losses of the house in function of the outdoor temperature (heat losses line). With the help of the heat pump manufacturer data (inlet water temperature assumed equal to 50°C), we can determine the balance point of the system (heat pump-house): $T_{OUTDOOR}$=-10°C and ϕ_{HO}=11.87 kW. The heat released by the radiators in these conditions is ϕ_{RAD}=10.31 kW and the heat delivered by the installed heat pump is ϕ=11.66 kW. This leads to conclude that the design point of the heat pump was about -10°C, i.e. allowing the heat pump to heat up the house without the need of a backup heater. This is consistent with the use of a capacity-controlled heat pump with injection cycle.

3.1.2 Heat pump performance

The heat pump performance is evaluated by using the model with the controller, i.e. by computing the heat released by the condenser and the electricity consumed by the heat pump for every time step the controller switches on the heat pump installation. Other information is available like the water temperature at the outlet of the condenser, the indoor temperature of the basement and first floor, etc. Results for April 15th are given in figure 5.

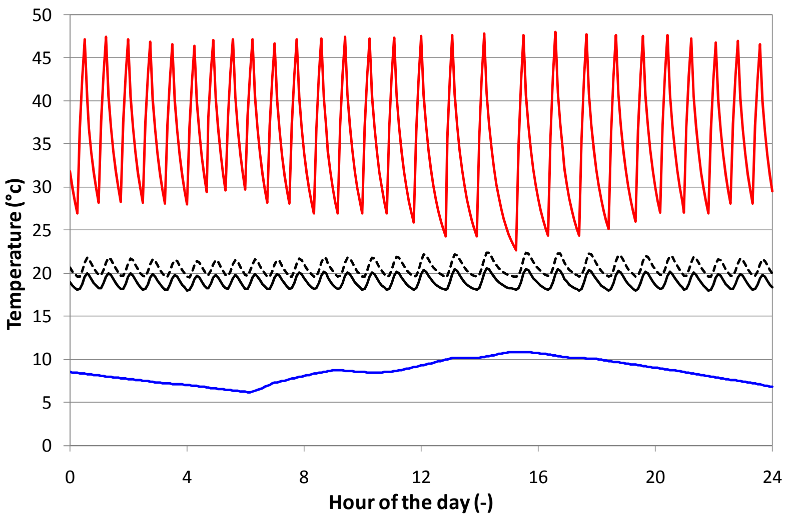

Figure 5: Simulation results for April 15th: condenser water outlet temperature (—), basement air temperature (—), 1st floor air temperature (…), outdoor temperature (—)

Figure 5 shows that the heating cycle frequency depends on the outdoor temperature and that the thermal inertia of the radiators is well accounted for. However, the heating cycle is short, letting suspect that the heat pump may be oversized. The indoor temperature oscillates around 19°C at the basement and around 21°C at the first floor what is not desired. This high first floor indoor temperature is due to the placement of too many radiators: the 8 radiators in the basement can deliver 10982 W for heat losses of 9037 W ($T_{OUTDOOR}$=-8°C) while the 3 radiators of the first floor can deliver 7518 W for heat losses of 1989 W ($T_{OUTDOOR}$=-8°C).
All the available information is then integrated to give overall values for one year. These annual quantities as well as the total running time are given in table 1 (Heat Q, Electric consumption E, SPF, running time RT, minimum basement air temperature T_{BMIN}, minimum 1st floor temperature T_{1MIN}, average condenser outlet water temperature T_{WIN}).

Table 1: Annual quantities for the installed heat pump system

Q (kWh)	E (kWh)	SPF (-)	RT (h)	T_{BMIN} (°C)	T_{1MIN} (°C)	T_{WIN} (°C)
27839	9735	2.86	2206	17.6	17.4	45.9

Table 1 shows that the total heat delivered to the house (27839 kWh) is similar to that calculated in §3.1.1 (27407 kWh) validating the simulation model with the controller. The running time is average (25% of the year) and the minimum temperatures for both floors are close to the minimum design temperature (18°C). The average water temperature in the radiators is quite low (45.9°C). The SPF is close to the target value of 2.88.

3.2 Parametric studies

3.2.1 Heat pump size

As mentioned above, the installed heat pump is perhaps oversized, leading to short heating cycles. A first study is therefore to run the model with lower capacity heat pumps. As real manufacturer data are not available, we have created low capacity heat pumps data by dividing the installed heat pump heat flow rate by a constant factor RF and by keeping the COP equal to the one of the installed heat pump. The reduction factor RF varies from 1.25 to 2. The results are given in table 2.

Table 2: Annual quantities for the different heat pump sizes

RF (-)	Q (kWh)	E (kWh)	SPF (-)	RT (h)	T_{BMIN} (°C)	T_{1MIN} (°C)	T_{WIN} (°C)
1	27839	9735	2.86	2206	17.6	17.4	45.9
1.25	27916	9682	2.88	2761	17.7	17.4	44.9
1.5	28124	9757	2.88	3337	17.8	17.4	44.7
2.0	28086	9388	2.99	4437	15.2	16.7	41.6

Table 2 shows that up to a reducing factor of 1.5, the SPF as well as the heat delivered to the house Q and the minimum indoor air temperatures T_{BMIN} and T_{1MIN} do not vary a lot. The running time RT increases and the condenser outlet water temperature decreases due to the downsizing of the heat pump. For the reducing factor of 2.0, the SPF increases but the minimum indoor air temperatures are lower which can lead to comfort problems (no electric backup heater is used). We can conclude that the choice of the size of the heat pump is easy since its capacity can vary in a range of 50% without causing comfort and performance problems. This large size range is due to the type of heat pump (capacity-controlled, injection cycle). Normally, the SPF should increase faster with the reducing factor due to the presence of longer heating cycles. This is not the case in our simulations because it was not possible to use a ‘short cycle’ penalty factor.

3.2.2 Heat pump type

In order to assess the conclusions of the previous section concerning the injection cycle, we have used a heat pump without injection cycle. The choice of the heat pump is the following: the balance point for the design is for $T_{OUTDOOR}$=-10°C and the heat pump manufacturer is the same. The final choice is an air-to-water heat pump with ϕ=9.15 kW at $T_{OUTDOOR}$=-10°C. The performances of the installed and new chosen heat pumps are given in figure 6. The results of the simulation are given in table 3.

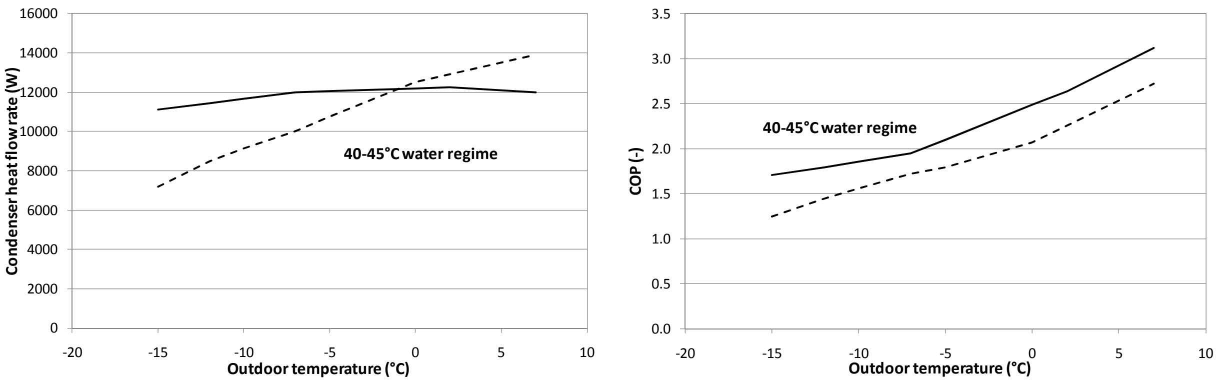

Figure 6: Condenser heat flow rate (left) and COP (right) of the installed heat pump (—) or the new heat pump without injection (…) for water regime 40-45°C

Table 3: Annual quantities for the two heat pump types

Type (-)	Q (kWh)	E (kWh)	SPF (-)	RT (h)	T_{BMIN} (°C)	T_{1MIN} (°C)	T_{WIN} (°C)
Installed	27839	9735	2.86	2206	17.6	17.4	45.9
Without injection	27853	11634	2.39	2111	17.8	17.4	46.3

Table 3 clearly shows that the injection cycle is responsible for a high SPF value by comparing it with a simple thermodynamic cycle without injection.

3.2.3 Radiators size/type/place

Another way of increasing the SPF is to change the radiators, for example by placing convector heaters (what has been done in mid-May 2010 in the house, see (Dumont et al. 2011)) or to increase the size of the radiators: this decreases the water temperature needed to heat up the house. In the model, that means increasing the UA value of equation (1). We have increased the UA value of the installed radiators by a factor IF of 1.5, 2 and 2.83. This last value relates to a case where the installed radiators with T_{WIN}=75°C (radiator design temperature) and the new radiators with T_{WIN}=45°C deliver the same heat flow rate. The results of the simulations are given in table 4.

Table 4: Annual quantities for the different radiator sizes

IF (-)	Q (kWh)	E (kWh)	SPF (-)	RT (h)	T_{BMIN} (°C)	T_{1MIN} (°C)	T_{WIN} (°C)
1	27839	9735	2.86	2206	17.6	17.4	45.9
1.5	27724	8348	3.32	2177	17.7	17.3	39.6
2.0	27642	7683	3.60	2169	17.7	17.3	36.0
2.83	27582	7114	3.88	2171	17.7	17.3	32.7

Table 4 shows that the main effect of increasing the size of the radiators is to decrease the water temperature at the condenser outlet T_{WIN}. This leads to a dramatic increase of the SPF of the heat pump, similar to what is obtained with a heating floor. A reasonable IF factor is

1.5: this gives an increase of SPF of 16% (from 2.86 to 3.32) and a decrease of the electric consumption of 14% (from 9735 kWh to 8348 kWh).
As mentioned in §3.1.2, there are certainly too many radiators in the first floor. A way of increasing the SPF is the exchange some of the radiators from the first floor with ones of the basement. If we exchange the radiator of the bathroom of the first floor with the radiator of the hall of the basement, the balance is better: the 8 radiators of the basement can now deliver 12364 W in place of 10982 W and the 3 radiators of the first floor can deliver 6136 W in place of 7518 W. The results of this change are given in Table 5.

Table 5: Annual quantities before and after radiator change

Type (-)	Q (kWh)	E (kWh)	SPF (-)	RT (h)	T_{BMIN} (°C)	T_{1MIN} (°C)	T_{WIN} (°C)
Installed	27839	9735	2.86	2206	17.6	17.4	45.9
After change	26992	9186	2.94	2132	17.6	17.4	44.8

Table 5 shows that the decrease of the radiators surface area in the first floor leads to a decrease of the heat delivered to the house without changing the indoor temperature of both floors. The increase of the radiators surface area in the basement leads to a small decrease of the water temperature and to a small increase of the SPF (2.94), now just above the target SPF (2.88).

3.2.4 Dwelling insulation level

As the replacement of the radiators is not always possible, another possibility is to decrease the heat losses of the dwelling by insulating it. Figure 7 shows the heat delivered by the installed radiators and by radiators with surface area increased by a factor IF=1.5. For the heat losses of the house (10 kW for $T_{OUTDOOR}$=-8°C), the water inlet temperature must be 72°C for the real radiators and 58°C for radiators of IF=1.5. In order to use the real radiators with T_{WIN}=58°C, the heat losses of the house must be decreased to about 6.74 kW, i.e. by increasing the house insulation level.

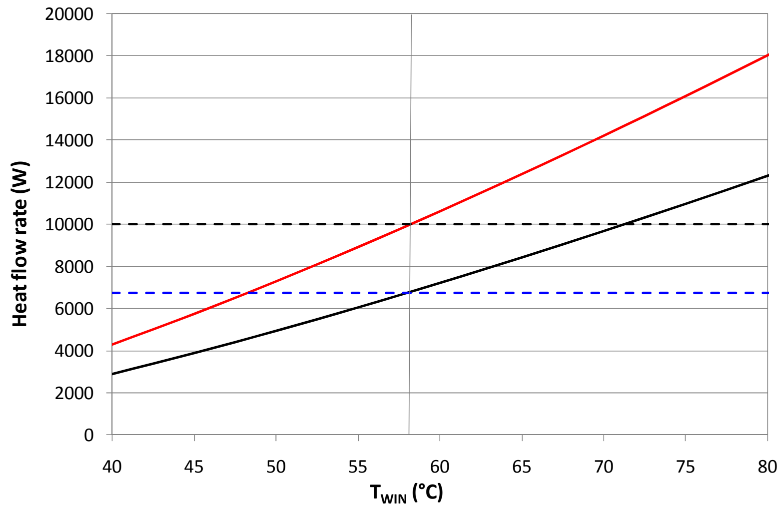

Figure 7: Heat delivered by the real radiators (—) and by the new radiators (—) for the real heat losses (…) and for the insulated house (…)

This insulation level is obtained by placing 3 cm of expanded polystyrene between the basement and the underground level, by adding 8 cm of mineral wool under the roof (total 20 cm) and by replacing the double glazing windows with new ones with U_{WIN}=1.66 W/(m^{2}K). The air infiltration rate is also decreased from 1.0 to 0.8 h^{-1}. These changes lead to an average heat transfer coefficient of the house U_{TOT}=0.55 W/(m^{2}K) and a SPF of 3.32. From a

SPF viewpoint, it is obvious that it is cheaper to replace the radiators than to insulate the house. From an energy consumption viewpoint, insulation is always welcome in order to decrease the energy bill, so that both solutions are useful.

4 CONCLUSION

The system model has first been used to simulate the heat demand of the house: the model developed in TRNSYS shows good agreement with the real heat demand. Second, the use of the radiator and control models leads to conclude that the installed heat pump is certainly oversized, that there is too many radiators in the first floor and that the annual SPF=2.86. Third, the parametric study clearly shows the advantage of using a high temperature heat pump with injection cycle: the choice of the heat pump size (keeping the same SPF) is large and the injection cycle allows to heat up the house without need of a backup heater while having a larger SPF than a non injection heat pump. In order to easily increase the SPF, an increase of the radiator UA value of 50% gives an increase of 16% of the SPF (3.32) and a decrease of 14% of the annual electric consumption. This SPF value can also be reached by a better insulation of the house and by replacing the double glazing windows, what is not very economical, but the advantage of insulation is also to decrease the annual electricity bill.

5 NOMENCLATURE

a_R	Radiator curve factor [W/K^3]
b_R	Radiator curve factor [W/K^2]
c_{PW}	Water specific heat at constant pressure [J/(kg K)]
c_R	Radiator curve factor [W/K]
m_W	Water mass in a radiator [kg]
q_{MW}	Water mass flow rate in a radiator [kg/s]
t	Time [s]
A	Radiator surface area [m^2]
A_{TOT}	House total heat losses surface area [m^2]
A_{WIN}	Windows total surface area [m^2]
E	Annual electricity consumption [kWh]
IF	Increase factor [-]
Q	Annual heat delivered to the house [kWh]
RF	Reduction factor [-]
RT	Annual running time of a heat pump [h]
SPF	Seasonal performance factor of a heat pump [-]
U	Overall heat transfer coefficient of a radiator [W/(m^2 K)]
U_{TOT}	Overall heat transfer coefficient of the house [W/(m^2 K)]
U_{WIN}	Overall heat transfer coefficient of the windows [W/(m^2 K)]
T_{BMIN}	Minimum indoor temperature in the basement [°C]
T_{INDOOR}	Indoor temperature [°C]
$T_{OUTDOOR}$	Outdoor temperature [°C]
T_{WIN}	Water temperature at the inlet of the radiator model [°C]
T_{WOUT}	Water temperature at the outlet of the radiator model [°C]
T_{WOUT2}	Water temperature at the outlet of the radiator capacity model [°C]
T_{1MIN}	Minimum indoor temperature in the first floor [°C]
ϕ	Condenser heat flow rate of a heat pump [W]
ϕ_{HO}	Heat losses of the house [W]
ϕ_{RAD}	Heat flow rate delivered by a radiator [W]

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