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ABSTRACT

The substitution of low-performance gas and fuel boilers by air to water electrical heat pumps is a solution to meet the energy challenge to reduce GHG dwellings emissions. Indeed, most dwelling emissions in Europe are due to heating and DHW generation with fossil fuels. Apart from low carbon emissions, high energy savings are expected from rated performances, but an AWHP may not deliver the expected efficiency because of a bad commissioning. Nowadays, these machines present a high number of parameters – over 40 on average – to be set during the installation, which makes this process very complex. Unfortunately, the parameter setting is a crucial step for the proper operation of the system throughout its life cycle. A non-optimal choice of AWHP parameters may lead to severe performance losses or discomfort.
The first part of the paper describes the functions and parameters that the installer must adjust for the commissioning phase. In a second step, the consequences of a non-optimal parameterization of an AWHP are evaluated.
This analysis is based on a computer model using Modelica language. The model consists of a heating system, installed in a typical detached dwelling. Simulations are run by pairing the heat pump with the dwelling and the heating system.
Simulations show the potential energy savings and the accuracy of indoor air control when control parameters, in particular the heating curve, are adapted to the dwelling and to the heating network. Final results confirm that an optimization of the parameterization of an AWHP makes a significant difference, in both energy savings and indoor air temperature control accuracy.

1. INTRODUCTION

The European Union aims to cutting its GHG emissions by 20 % by the year 2020 (compared to 1990 values), as exposed by the Commission of the European Communities (2008). A major part of these emissions is due to heating and DHW generation in the building sector; indeed, in France it represents about 25% of total CO_2 emissions and 40% of the final energy consumption as shown by the French Environment and Energy Management Agency (2012). High performance insulation in new buildings aims to reduce their thermal energy consumption; however, the bulk of the building stock in 2050 is already built. Therefore, the main challenge to curb GHG emissions in the building sector is to reduce the energy consumption of the existing buildings. For this reason, France is making efforts to foster the replacement of the old gas/fuel boilers by more environmentally-friendly technologies such as heat pumps.

Over the last few years, heat pump performances have improved at full capacity standard conditions, but also at off design rating conditions. With the increased penetration of variable speed compressors, AWHP reach higher seasonal performance factor ratings. However, the operation adaption of an AWHP is not only limited to capacity control.

Table 1: Modifiable HP number of parameters for eight AWHP manufacturers

AWHP brand	a	b	c	d	e	f	g	h
Number of parameters to be modified by the installer	61	21	191	54	40	50	91	54

This paper first describes the parameters to be set for AWHP operation by explaining their purpose and impact on the AWHP operation. Secondly, an energy and comfort analysis is carried out in order to compare the performance of the same AWHP with different parameter settings.

2. CONTROL PARAMETERS DESCRIPTION

Heat pumps account for a great number of parameters to be set during commissioning (over 40 on average). Table 1 shows a comparison among the number of control parameters to be set by the installer of eight different AWHP (each product corresponds to one manufacturer) and Table 2 summarizes all these parameters by categories. The setting of so many parameters may add too much complexity at the time of installation and lead to incorrect / sub-optimal settings.

AWHP operation is determined by a set of parameters, whose purpose is to adapt the heat pump capacity and performance to the characteristics of the building, to the heating distribution network and to the users' preferences. Parameters are adjusted at the time of the first commissioning of the heat pump. A non-optimal choice in the combination of these settings may lead to discomfort and overconsumption. However, the best configuration is not known a priori as the thermal characteristics and heating system in all dwellings differ. Indeed, the combination of the building insulation, weather conditions, type and size of heating distribution network, as well as users' preferences is so great that the thermal behavior of each dwelling is unique. Therefore, parameter setting is under the responsibility of the installer.

Parameters are grouped below according to four categories: space heating (section 2.1), generation of domestic sanitary hot water (DHW) (section 2.2), AWHP operation (section 2.3) and users' preferences (section 2.4).

2.1 Space heating parameters

In the case of an AWHP, water is the medium which delivers the heat throughout the heating network of the building. According to the building and heating network characteristics, the AWHP must deliver the correct water temperature in order to meet the heat demand. As external temperature changes, the dwelling heat demand also changes. Therefore, there is a relationship between the outdoor air temperature, the water inlet temperature and the heating network. This relationship, called *heating curve (HC)* by Béranger (2009), determines the proper water temperature required to ensure comfortable indoor conditions as a function of the outdoor air temperature.

Depending on the heat pump, the setting of these heating curves can vary noticeably. Some manufacturers propose several already pre-configured HC for different types of heat emitters. In this case they also include another parameter to vary the offset of the HC (vertical and horizontal displacement). Other manufacturers allow users to set themselves the HC as a straight line fixed by two end points: the heating-water-temperature corresponding to the lowest outdoor temperature and the heating-water-temperature which corresponds to non-heating temperature. A third kind of AWHP manufacturer presents a parameter to set the maximum heat losses of the building (which will determine the HC). In all cases, the heat pump will run tracking the water outlet temperature fixed by the HC.

Apart from water temperature control, indoor air temperature must be managed in order to maintain the desired set-point. Local control can be managed either by thermostatic valves in each radiator and/or by an indoor air thermostat typically located in the living room.

Table 2 : AWHP installation parameters summary

Space heating parameters	Indoor air temperatures	Comfort (usual set point)
		Reduced (eco mode)
		Max temperature to stop AWHP
		Thermostat installation
	Heating curve	Choice between several pre-set heating curves depending on the installed heat emitters (several types)
		Vertical and horizontal displacement (Offset)
		Straight line
		Maximum heat losses of the building
	Outdoor air temperatures	Minimal temperature for AWHP to run in thermodynamic mode
		Temperature to switch off heating
	Electric backup heater	Outdoor air temperature to authorize its operation
		Outlet water temperature to authorize its operation
		Minimal time heater must be off
		Heater delay time
Generation of domestic sanitary hot water (DHW)	Temperatures	Comfort (usual set point)
		Reduced
		Maximum outlet water temperature of AWHP for DHW
		Water tank temperature dead band
	Electric booster heater	Minimal time booster must be off
		Booster delay time
	DHW and heating management	Up to 15 parameters (not included in this study)
Defrost and compressor control parameters	Defrost	Minimal and maximal duration
		Evaporator surface temperature to start and stop the process
		Manual defrosting
		Minimal water inlet temperature to allow the process
	Compressor	Minimal time compressor must be running
		Minimal time compressor must be switched off
User's preferences	Temperatures and timing	Indoor air temperatures depending on different schedules (several temperatures and time parameters)
		DHW temperature depending on user's habits (several parameters not included in this study)

Some manufacturers take into account the feedback of the thermostat in order to optimize the performance of the heat pump. Dead bands from 0.5 K to 2 K around the set-point allow an ambient temperature control by switching the AWHP compressor on and off or adapting the compressor speed. However, an inappropriate placement of the indoor air temperature sensor or a non-appropriate combination of control devices (thermostatic valves and ambient thermostat in the same room) may lead to severe performance losses and heat pump dysfunctions, as commented in Atlantic (2012). Few manufacturers include an automatic adaptation of the heating curve to the dwelling in their regulation. For this reason, a parameter sets the proportion between outdoor and indoor air temperatures to be taken into account for the heat pump control. Nevertheless, in the installation notice it is highly recommended not to activate this function as it may produce dysfunctions.

When the AWHP manages indoor air temperature, manufacturers offer different air temperature set-points in order to comply with the users' habits and preferences, such as comfort and reduced ambient temperature (also called eco mode) set points. Maximum indoor heating temperature is another parameter that limits a possible overconsumption due to inappropriate parameterization.

The decrease of AWHP heating capacity at low temperatures (cf. Figure 1) can be mitigated thanks to a backup electrical heater situated downstream the condenser. In order to reduce the power peaks due to its operation, some control parameters can be adjusted: the outdoor temperature to authorize its connection (T_{backup}, Figure 1), the minimal off period between backup operations, the delay time before it switches on, or the water temperature dead bands to control the on/off switching strategy. Besides, an AWHP also presents safety parameters as the maximum heating water outlet temperature, the maximum outdoor temperature to run heating and the minimum outdoor temperature at which the heat pump can run ($T_{min\ AWHP}$, Figure 1).

2.2 Domestic Hot Water parameters

The DHW generation can be managed by the heat pump if a tank is connected. Most AWHP's alternate between heating and DHW functions, i.e. hot outlet water from the heat pump will be distributed either to the space heating network or to the reservoir tank by a three way valve. Typical parameters for DHW are comfort and reduced temperature set-points on the tank, which determine the water outlet temperature set-point for the heat pump during DHW generation. To avoid continuous DHW operation, water tank temperature dead bands are included in the parameters.

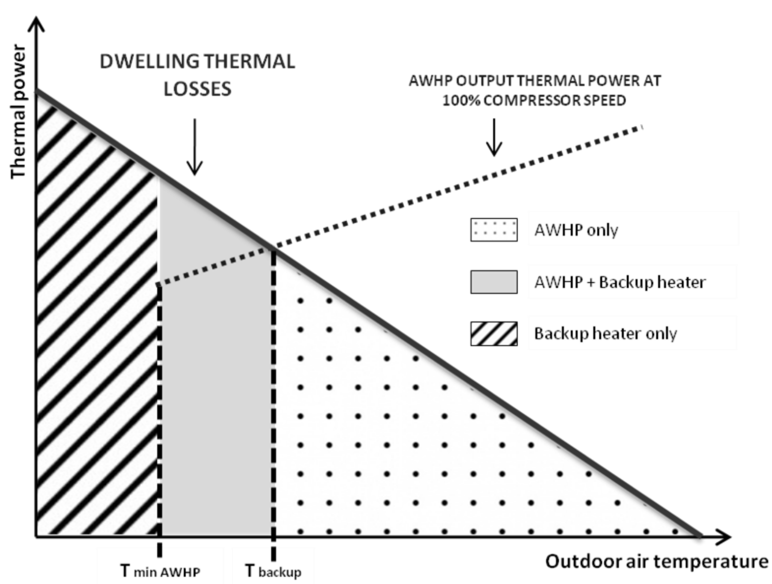

Figure 1: Dwelling thermal losses as a function of outdoor air temperature

Manufacturers present different operating modes to manage the DHW generation and heating, especially since at low outdoor temperatures both demands are likely to be simultaneous. Most of them install an electrical heater (booster) immersed in the tank to decrease heating-up time. To optimize DHW production, up to 15 parameters are offered. They are not considered in this study because the AWHP is connected only in heating mode, and DHW is considered to be generated by an external source.

2.3 Defrost and compressor control parameters

As shown in Malaspina *et al*. (2004), heat pump performances increase in mild outdoor temperatures but they also decrease as outdoor temperature falls. Moreover, as stated in Argaud (2001), external air relative humidity reduces performance due to defrosting processes: AWHP must eliminate the frost accumulation at the evaporator, which has usually most impact on performance at air outdoor temperatures of between -5°C and 5°C.

In order to reduce this decrease in performance, heat pumps also include control parameters dedicated to improve defrosting. For instance, some manufacturers allow minimal and maximal defrost duration setting, evaporator surface temperature to start and stop the process, the possibility of running the process manually or the minimal water inlet temperature to allow defrosting (to prioritize comfort versus efficiency).

Conversely, the higher the outdoor temperature, the closer the AWHP will be to its nominal heating capacity. Nevertheless, at mild outdoor temperatures (>5ºC) an AWHP provides a higher thermal power output than that required by the dwelling (cf. Figure 1). Thanks to variable speed technology, compressors can adjust their frequency in order to comply with the heat demand at any time. Nevertheless, a minimal compressor speed limits minimal heating output, leading to an on/off operation at very low loads. The compressor's life may be adversely affected if the anti short cycle timer is not well parameterized. For this purpose, control parameters such as the minimum compressor running time and stopping times are set by the installer.

2.4 Users' preferences parameters

Timer parameters enable users to customize the set point temperature schedule based on their habits and preferences. Anticipating temperature variations may help to control the desired temperature at the desired time. For instance, switching off the heat pump and taking advantage of the thermal inertia of the dwelling may lead to important energy savings. Furthermore, gradually switching on the output power of the heat pump may limit the peak power consumption when a shifting temperature is scheduled. DHW tank temperature can also be customized to be adapted to the occupants' presence, in order to anticipate its generation before users may need it.

Most of the parameters presented in the sections above are directly related to the characteristics of the building and occupants' habits. Therefore, the commissioning process includes an important phase to adapt around 40 parameters on average to ensure a proper AWHP operation. The following section will evaluate the impact on comfort and performances of the variation of one of the most common modifiable parameters: the heating curve. This study is focused on existing buildings where AWHP replace obsolete boilers.

3. HEATING SYSTEM PERFORMANCES STUDY

To evaluate the impact of a non-optimal parameterization of an AWHP, a heating system performances study has been undertaken. This study is based on the computer simulation of an AWHP dynamic model, connected to a water heating network, which is installed in a typical detached dwelling. Several configuration cases are used to compare possible mistaken configurations of control parameters and size of heating networks.

3.1 Simulations description

The computer model consists of the house, the distribution network, the controller system and the AWHP. The simulated dwelling is a typical detached house with a surface of 100 m², built between 1974 and 1982. The AWHP has a standard rating heating capacity of 9 kW (measured at an outdoor temperature of 7 °C and an outlet water temperature of 35 °C, following the rating European standard (CEN, 2013)). AWHP includes a variable speed drive compressor which operates with a minimum operating frequency of 20% of the frequency at the maximum rotation capacity. Simulations have been carried out using yearly weather data from Paris provided by Meteo-France (2014).

In order to reduce the simulation time, the chosen house model considers the heating volume as one single zone of 100 m². As a consequence, the water heating network is also simplified with the use of one radiator with a thermal nominal power to confront the heat losses of the dwelling following the European radiator standard (CEN, 1996). This radiator is connected to the heat pump by pipes with the size and length equivalent to the total heating distribution network (15 m and U = 0.6 $W.m^{-1}K^{-1}$) of a dwelling of that same surface.

House insulation materials and width fulfill the requirements of the 1974 French building regulation, redacted by the French Ministry of Ecology, Sustainable Development and Energy (1974). In agreement with the French Agency for Environment and Energy Management (2012), the rating for thermal losses are calculated for an indoor air temperature of 19°C and for the average lowest outdoor air temperature registered over the years in the chosen region. Hence, the nominal thermal losses of the dwelling are 7 kW at an outdoor temperature of -7°C. Therefore, heat demand should be met with radiators of a nominal heating power of 8 kW (15% over sizing is considered in order to guarantee unexpected very low temperatures or heating setback) for an inlet/outlet water temperature range of 55/45°C. Radiators include thermostatic valves at the inlet.

3.2 Sensitivity analysis of control parameters

The heating curve is the control parameter with the highest impact on the AWHP operation. As commented in section 2.1, an electrical backup heater can complement the AWHP operation at cold temperatures. However, its activation depends on parameterization. The third control parameter assessed is the configuration of the indoor air control. The temperature regulation will be either by thermostatic valves or by an air indoor thermostat.

Section 1 highlighted the opportunity to reduce GHG by replacing the existing gas or fuel boilers by AWHP. Usually, gas and fuel boilers operate with a maximum water outlet temperature of 75°C. Nevertheless, most AWHP, as stated in Bernier, J. 2007, are limited to 55 °C at most. Hence, heat emitters must be adapted in consequence. In order to show the impact of not adapting the radiators after the installation of an AWHP, two radiator sizes have been chosen: 8 kW for a water temperature range of 75/65 °C (case of emitters not changed) and 8 kW for a temperature range of 55/45 °C (i.e. 13 kW for a temperature range of 75/65°C).

For this study, four different heating curves have been evaluated (cf. Figure 2).

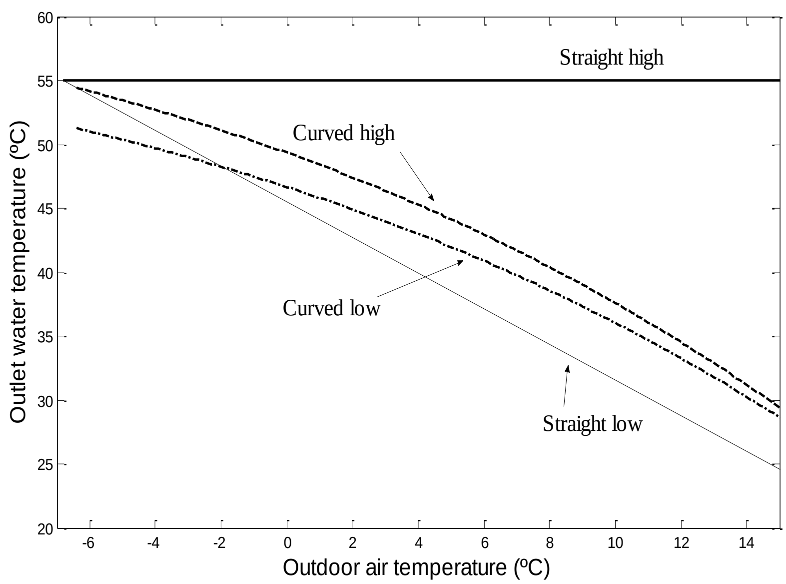

Figure 2: Heating curves evaluated

Two of them (curves “Curved high” and “Curved low” in Figure 2) are those proposed by manufacturers as preset curves. “Straight low” curve is a straight HC set by the temperature limits as the endpoints; this is the most common HC configuration found. Curve “Straight high” is set to the maximum outlet water temperature of the AWHP. The choice of this HC is because, after field monitoring, some AWHP have been found to be configured this way.

3.3 Performance study

To evaluate the performance of the heating system, two main indicators must be taken into account to compare the different heating systems’ configurations: the temperature set point deviation and the annual energy consumption.

Temperature set point deviation is expressed as the average number of Kelvin-hours per day (K.h/day) (Hoogmartens, J. *et al*. 2011) which exceed (above or below) the temperature set point in 1.5 °C (i.e. below 17.5 °C and above 21.5 °C). This evaluation was carried out by measuring overheating and under-heating throughout the heating season (1st October to 31st May). This indoor air temperature control accuracy method does not take into account the measurements when the outdoor air temperature is above 16 °C. This is to avoid results produced by outdoor temperature and not by a poor temperature control.

Conversely, for the energy performance study, energy consumed is calculated as the sum of the electric consumption of the AWHP (the electricity consumed by the compressor, the controller, the water pump and the outdoor fan) and the electric consumption of the electrical backup heater. In order to compare the different case studies, the seasonal performance factor (SPF) was calculated as the ratio between the total heat produced and the total electricity consumed.

Temperature set point deviation evaluation results

Results where the radiators do not have the surface adapted have been discarded for further studies, as it is considered that these systems do not fulfill the aim of heating (temperature set point deviations below -20 K.h/day).

For other cases, results have been compared by taking into account the air indoor control, the activation of the backup heater and the heating curve chosen. Indoor air control does not make a significant difference to energy consumption nor temperature control accuracy; however, it does influence the number of compressor cycles per year (cf. Table 3).

Thermostatic valves will reduce the mass flow rate entering the radiator when necessary. Hence, the water temperature difference between the outlet and inlet of the AWHP will be reduced. Consequently, the compressor will stop more often as it will achieve its minimum load easily. For these reasons results on Figure 3 focus on thermostat air control, which has less influence on the number of compressor cycles.

Tradeoff between the SPF and the temperature set point deviation can be seen on the left hand side of Figure 3. An average temperature set point deviation of - 0.75 K.h/day is present when backup is not authorized (non bold markers); on the other hand, negligible temperature set point deviations are achieved thanks to a backup operation. The best SPF is related to the heating curve “Straight low”, though with average temperature set point deviations from - 0.3 to - 0.7 K.h/day. For the results with negligible temperature set point deviations (~ 0 K.h/day), heating curve “Curved high” achieve the best performances.

Table 3 : Number of compressor cycles per year depending on the indoor air control

		THERMOSTAT		**TH. VALVES**	
		Backup	**No backup**	**Backup**	**No backup**
Heating Curve	**Straight high**	2851	2257	15721	15439
	Curved high	2025	1890	12916	12922
	Straight low	5162	5140	11281	11266
	Curved low	1671	1585	12421	12428

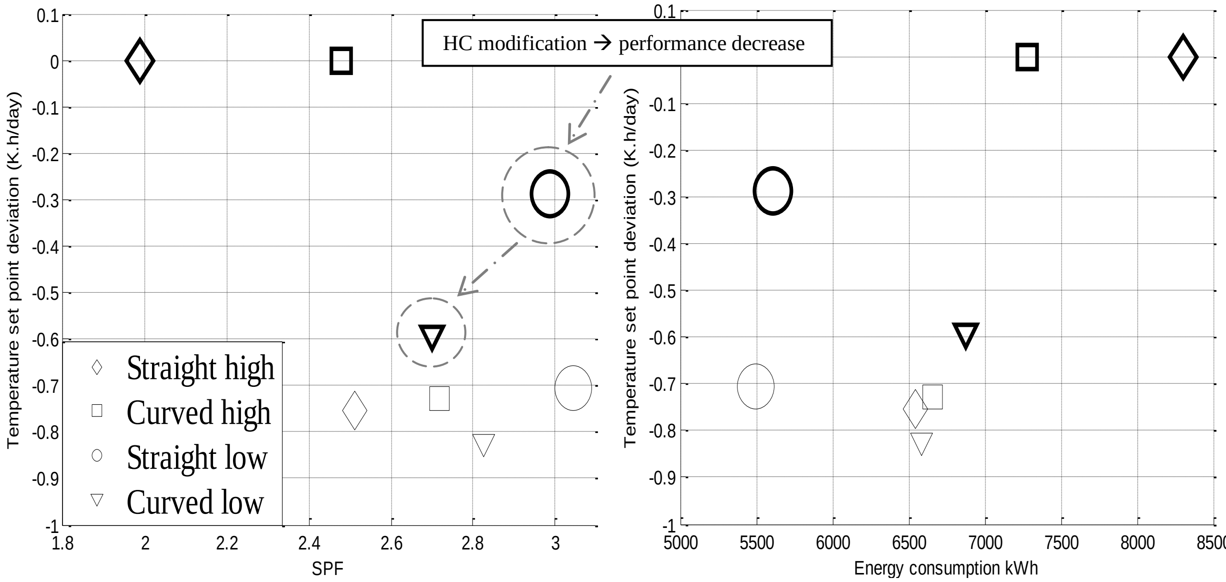

Figure 3: Trade-off between SPF, annual energy consumption and temperature set point deviation. Thermostat indoor air control. The size of the markers is related to the number of annual compressor cycles. Bold markers represent simulations with electric connected backup heater

Even at best performances ("Straight low" heating curve) the slightly negative average temperature set point deviation may encourage users to modify the heating curve settings (left hand side of Figure 4 shows the temperature range concerned). However, air control and performance can be adversely affected if the heating curve is wrongly moved. For instance, swapping from "Straight low" to "Curved low" will harm the situation as shown on Figure 3.

Energy consumption results

The tradeoff between the temperature set point deviation and energy consumption is shown on the right hand side of Figure 3. The highest electricity consumption (above 8 MWh/year) is associated with the heating curve "Straight high". On the other hand, the lowest consumption is that of HC "Straight low", which indicates this HC as the best choice. This configuration shows a final energy consumption of 5.6 MWh/year, a SPF of 2.98 and 5162 compressor cycles per year. Even though, the number of cycles is much higher than for other configurations (cf. Table 3). Actually, the number of cycles can reach up to 14 per hour at an outdoor temperature of 15ºC (cf. Figure 4). Users may reduce this situation by modifying the HC configuration; however, as shown on Figure 3, this may lead to performance losses. A solution may be to modify the parameter which establishes the maximum outdoor temperature for heating. Limited heating may lead to lengthen compressor life as well as a reduction in energy consumption when an AWHP operation is unnecessary.

Concerning the highest consumptions, analysis results show that within a total electricity consumption of 8.3 MWh ("Straight high" HC + heater + thermostat), 34% of this electricity is consumed by the backup heater. This can be explained because the water outlet temperature set point is set to maximum, so the AWHP will authorize the backup heater to run more often. On the other side, the lowest consumption is 5.4 MWh (case of the HC "Straight low" without backup heater and air indoor temperature regulation by thermostatic valves); however, the number of cycles per year (11281) is much higher than for other configurations (cf. Table 3).

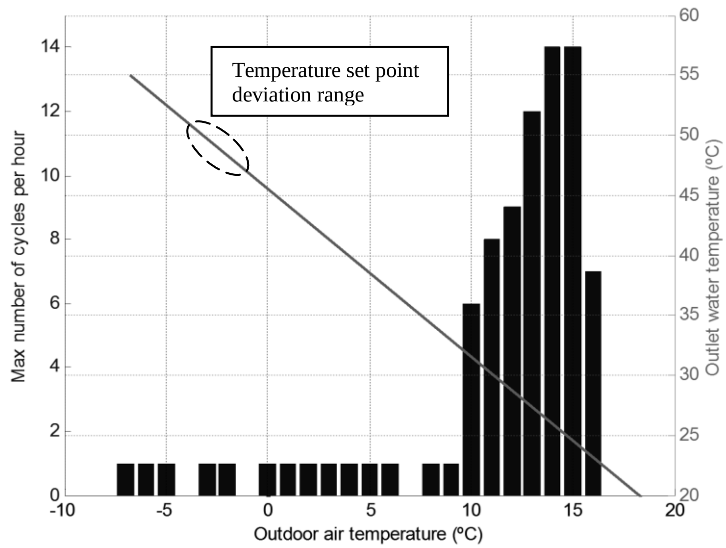

Figure 4 Temperature set point deviation range and number of compressor cycles for the results of the straight low HC with thermostat air control and backup heater.

4. CONCLUSIONS

After the assessment of different parameters' configurations, this paper has shown that an incorrect parameter setting can lead to severe performance losses and a high degree of occupants' discomfort. In fact, if the heating curve is not adapted to the heating system, energy consumption can be 50% higher than in the best performances configurations (while respecting the indoor air temperature set point between the given limits). Results show that the SPF can vary from 1.9 to 3.04 depending on the different combinations of heating curves configurations, indoor air control systems and electric backup heater authorization.

Besides, even if a heating curve ensures acceptable energy consumption, a slight negative temperature set point deviation would encourage users to modify the settings. A poor modification of the parameters will lead to higher temperature deviations (and possibly higher consumptions). This situation may lead to generalized discomfort and unnecessary electricity consumption. Besides, problems such as compressor cycling could be improved if a correct parameter setting is adapted along the AWHP life cycle.

To conclude, this paper has revealed that the non-optimal parameterization of an AWHP severely affects the performances of the heating system. Bad configurations lead to unaccepted temperature set point deviations, unnecessary high electricity consumptions and a decrease in AWHP life due to compressor cycling. Hence, the adaption of parameters to the dwelling and the heating network are likely to provide performance improvements and air temperature control accuracy.

NOMENCLATURE

AWHP	Air to Water Heat Pump
ADEME	French Agency for Environment and Energy Management
DHW	Domestic Hot Water
GHG	Green House Gases
HC	Heating Curve
HP	Heat Pump
K.h	Kelvin hours
SPF	Seasonal Performance Factor
U	Overall heat transfer coefficient

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