Influence of Internal Control Simplifications in Heat Pump System Modelling for Energy Flexibility Evaluations

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Abstract

Heat pump internal control strategies are frequently neglected, while the impact remains uncertain. This paper studies the short- and long-term effects of those strategies via simulation of a water-to-water heat pump. Neglecting these strategies caused non-negligible effects and profile modification. The electrical heat pump power was compared between simplified models and more detailed models that are able to accurately represent the internal strategies. It was shown that for 42 – 86 \% of the year, the electrical heat pump power of the simplified models was within +/- 10 \% of the most detailed model. As a second part, a flexible control with a spot tariff was applied to the heat pump. Compared to a classical approach to heat pump modelling with only minimum modulation, results again proved the importance of modelling heat pump internal control strategies.

Key Innovations

- Inclusion of internal control strategies in heat pumps
- Modelling influence of simplifications in heat pump control systems
- Dynamic pricing flexibility with heat pump systems

Practical Implications

Always consider heat pump internal control strategies as both long- and short-term behaviour will differ

Always consider heat pump cycling effects with heat losses to the environment

Avoid using only full-load heat pump performance data

Introduction

The increasing growth of renewable energy resources increases the need for flexibility on the energy grid. While currently flexibility is mostly obtained from energy producers and industrial customers, households could also play a major role in the future (Andreiadou et al., 2018). Modulating electric driven heat pumps (MEDHP) can further support the energy transition and are considered as a key technology to couple the heat and electricity sector. In combination with thermal energy storages, heat pumps (HP) offer the ability to adapt their load profile in order to provide flexibility to different stakeholders (Arteconi & Polonara, 2018).

While the potential of flexible HP control has already been thoroughly studied in literature, the modelling approaches for the representation of its real behaviour differ. Fuentes et al. (2016), Fuentes et al. (2017) and Fuentes & Salom (2019) presented a validated on/off ground-source HP model, while experiments indicated the relevance of considering the dynamic behaviour of the HP and especially during cycling conditions. In addition, Dongellini & Morini (2019) compared cycling losses of single-stage, multi-stage and MEDHP and, indicated that dynamic and small time-step HP models are needed for detailed performance analysis during cycling conditions.

An accurate model able to represent the real HP behaviour in this context, including the internal control strategies, is novel. Neglecting those internal strategies will result in a different behaviour when compared to a real system and therefore, the provision of flexibility will differ (Clauß & Georges, 2019; Fischer & Madani, 2017 and Fuentes et al., 2017). Claus & Georges (2019) described HP model complexity with the focus on energy flexibility, analysed control simplifications in Demand Response (DR) with HP and provided a more accurate model. Several modelling simplifications were noticed by the authors, while they analysed several Proportional (P) and Proportional-Integral (PI) compressor controllers and stated that for analysing short-term and DR behaviour the inclusion of internal control strategies is necessary. In addition, Lindahl (2020) compared direct with indirect HP control in a hardware-in-the-loop (HIL) approach and clearly showed the influence of the internal control strategies. Bypassing the internal controller with a tailor-made solution caused a profile agreement in which the compressor power was within +/- 10 \% for 97 \% of the time, while indirect control via the manufacturer’s controller reached only 64 \% requested profile agreement.

The analysis of the state-of-the-art shows that in some cases, constraints such as part-load performance data, minimum HP on/off-times, minimum modulation rates, a temperature hysteresis for on/off control and domestic hot water (DHW) prioritisation are integrated, while more advanced strategies are frequently neglected. Those advanced strategies include minimum DHW on/off-times, condenser pump control and back-up heater control. In addition, most studies directly control the modulation capabilities of the HP, while with market-available heat pumps of today, this is hardly achievable. Although, inclusion of internal control is not always straightforward as it regularly requires additional manufacturer data. To summarise, neglecting internal control strategies introduces uncertainties to the real HP behaviour, especially during the provision of flexibility. In particular,
HIL analysis allows improved evaluations thanks to a combination of tests and models. In this context, this paper presents a performance map based HP model of a real HP where internal control is modelled in Modelica. The goal of this paper is twofold. Firstly, simplifications in internal HP control strategies are investigated. Control blocks are introduced step-by-step and their influence is investigated, both in short- and long-term, on the basis of a real HP. Secondly, the proposed HP model is used in a DR approach in which a spot tariff is combined with a predictive rule-based control. In future work, the heat pump models will be used in a HIL framework where the HP is operated with different flexible control strategies.

**Methods**

**Heat pump and internal control modelling**

The HP models, used in this paper, are discussed below. The models extend from the ground-source HP model from the Modelica IDEAS library (Jorissen et al., 2018). The models have an evaporator and condenser heat exchanger water volume and a port for environmental heat losses, which makes it already possible to consider dynamic effects of the heat exchangers. An overview of the control blocks and related parameters can be found in Figure 1 and Table 1, respectively, while the HP under consideration is a Daikin type EGSA06D9W (Daikin, 2020). Yearly simulations with one minute time steps are performed on a Flemish residential single-family building in Dymola. Depending on the case, the HP uses only full-load data or is also provided with part-load data. Control blocks are added step-by-step and as such, the influence of each block is investigated, both in short- and long-term.

Both full load and part-load HP modelling approaches use the thermal condenser and electrical compressor power.

**Table 1: Internal control parameter settings**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum compressor cycles</td>
<td>6 per hour</td>
</tr>
<tr>
<td>Minimum DHW on-time</td>
<td>1 minute</td>
</tr>
<tr>
<td>Minimum DHW off-time</td>
<td>30 minutes</td>
</tr>
<tr>
<td>Maximum DHW on-time</td>
<td>Case dependent: 30 or 60 minutes or weather-dependent as shown in Figure 2. During anti-legionella cycles: 125 minutes</td>
</tr>
</tbody>
</table>

**Figure 1: Flowchart internal control strategies**

Simplified HP models regularly have a modulation input where modulation is performed between 0 % and 100 %, while only full load data is used. In such an approach, the performance tables are interpolated via the evaporator inlet and condenser outlet temperatures. Afterwards, the condenser power is multiplied by the modulation input and as such, variations due to efficiency changes during capacity control are not considered. In those simplified models, no internal control strategies are considered.

**Variable capacity HP model: using only part-load data**

This model uses part-load data from five modulation levels, namely 30 %, 50 %, 70 %, 90 % and 100 % and hence, multi-dimensional interpolation with evaporator inlet and condenser outlet temperatures is used.

**Internal control: minimum modulation**

After determining the requested compressor modulation modreq HP to reach the desired outlet temperature, modreq HP is limited between a minimum and maximum rate. When in between those limits, the HP performs full modulation capabilities. When lower modulation rates are requested, the HP performs on/off cycles. A condenser outlet temperature hysteresis is then used to determine if the HP should be on or off. The minimum modulation rate for the HP under consideration is condenser outlet temperature dependent and this has also been modelled.

**Internal control: domestic hot water prioritisation**

Next to space heating (SH), a HP could provide DHW as well. Due to power and temperature limitations, a DHW tank and back-up heater (BHU) are regularly included. The control block uses a DHW and SH request, prioritises DHW and changes the position of a three-way valve. Minimum DHW on- and off-times are also considered to
prevent short DHW cycles and to ensure SH comfort as well. In case of too long DHW cycles, the three-way valve switches to SH and if necessary, after a minimum time, the DHW cycle starts again. Investigated maximum DHW on-times are 30 minutes, 60 minutes and weather-dependent control. In the latter case, the control is realised as described in the HP manual and illustrated in Figure 2. A second check is made to determine if the compressor or BUH are allowed to work. During SH, the compressor and BUH can operate in series. The compressor will heat the condenser water to its maximum allowed temperature, while the BUH delivers additional power to reach the final temperature setpoint. If the temperature setpoint is below 55 °C, only the compressor will work. During DHW, the compressor will warm up the tank until the requested temperature or until 53 °C as a tank temperature is reached. For higher requested tank temperatures, only the BUH can be used. Compared to the tank temperature setpoint, 2 °C higher supply temperatures were used.

**Figure 2: Weather dependency of DHW on-time**

Moreover, a weekly anti-legionella cycle was applied. Starting at Sunday 0h00, the tank is heated until 60 °C and afterwards, a timer is started. 55 °C should be maintained for 40 minutes and if the tank temperature drops below 55 °C, the timer resets and the cycle starts again. A maximum DHW on-time of 125 minutes is used to ensure cycling reliability and end-user’s health. As soon as one cycle is accomplished or if no full cycle is performed within four hours, normal operation is again considered.

**Internal control: back-up heater operation**

Back-up heaters regularly do not use continuous modulation and according the HP manual, discrete power steps of 1 kW are used. A two-degrees temperature hysteresis on the BUH outlet is applied to keep the temperature close to the setpoint. When the upper outlet temperature limit is reached, a 1 kW reduction is applied.

**Internal control: compressor runtime controller**

Due to less critical operation, the BUH is not equipped with a runtime controller. For the compressor, a minimum on/off-time is considered. Only safety reasons (too low evaporator or too high condenser temperatures) can cause to neglect these minimum on/off-times.

**Internal control: condenser pump control**

In this study, the evaporator is supplied with a constant temperature and constant flow rate. For the condenser, a modulating pump was used to maintain a constant temperature difference between HP inlet and outlet via two PI controllers. A slow and fast PI controller were used for the temperature difference and the pump speed, respectively. Manufacturer’s performance curves were used for the condenser pump, while a minimum flow rate was assured via additional constraints. To replicate the real behaviour of the underfloor heating system, closing valves and a differential pressure valve were also used.

**Case study**

A detached residential single-family building with a net floor area of 194 m² was considered. The building is in compliance with the 2020 Flemish building rules according Flemish Government & Flemish Energy Agency (VEA) (2018) and Flemish Energy Agency (VEA) (2020). Specifications can be found in Table 2. Figure 3 shows a hydronic overview, in which the direct connection of the underfloor heating could be noticed. As required by the HP manufacturer, a minimum system volume of 20 l is foreseen to limit the number of HP cycles and it should always be available, even if no heat is requested. Typical Belgian weather data was used.

**Figure 3: Overview hydronic circuit and case study**

A DHW profile of 100 l/day at 60 °C was generated via DHWcalc (Bleys, 2017; Jordan et al., 2017). The profile is adapted to a draw-off at 40 °C and corrections for lower or higher extraction temperatures are made as well.

**Table 2: Details reference building**

| U-value of walls, floor and roof | 0.24 W/m².K |
| U-value of doors | 1.45 W/m².K |
| Total air changes per hour | 0.51 h⁻¹ |
| Number of floors/thermal zones | 2 |
| Nominal heat loss at -8 °C outside | 9.4 kW |
| Type of heating system | Underfloor heating |
| Water supply/return at -8 °C outside | 37 °C/32 °C |

A 4000 kWh electricity profile for general appliances was generated via LoadProfileGenerator of Pflugradt (2020), while 6 kWp PV was used to cover the general electricity consumption and part of the HP consumption. The PV system is thus not able to cover the total electricity consumption and this PV power limitation is chosen to limit the installed PV power and future capacity tariffs will probably further limit high PV power installations. The self-consumption (SCR) and self-sufficiency rate (SSR) are calculated via (1) and (2), respectively.

\[
SCR = \frac{\sum_{t=0}^{t=\text{end}} P_{\text{PV consumed within household}}}{\sum_{t=0}^{t=\text{end}} P_{\text{PV, t}}} \tag{1}
\]

\[
SSR = \frac{\sum_{t=0}^{t=\text{end}} P_{\text{PV consumed within household}}}{\sum_{t=0}^{t=\text{end}} P_{\text{total household power, t}}} \tag{2}
\]
Figure 4: Weather dependent control for space heating

A case-overview in which DHW was always prioritised:

1. Only full load data without condenser heat losses or any internal control strategy and usage of a constant pump flow rate for the evaporator and condenser
2. Extension of case 1, with condenser heat losses
3. Using part-load data with condenser heat losses
4. Extension of case 3, with minimum modulation
5. Extension of case 4, with minimum on/off-times
6. Extension of case 5, with minimum DHW on/off-times and 60 minutes as maximum DHW on-time
7. Extension of case 6, with discretised BUH control
8. Extension of case 7, with condenser pump control to keep 5 °C temperature difference in DHW and SH
9. Extension of case 8, SH pump controls a weather dependent temperature difference as Figure 4 shows
10. Extension of case 9, but instead of 60 minutes as maximum DHW on-time, 30 minutes are considered
11. Extension of case 9, with a weather dependent maximum DHW on-time as shown in Figure 2
12. Extension of case 11, with anti-legionella cycles
13. Extension of case 4, with flexible control
14. Extension of case 12, with flexible control

The second part uses a predictive rule-based control (PRBC) with spot prices (SP) with the approach proposed by Clauß et al. (2019). PRBC uses future SP in order to favour the HP operation to certain time slots via rule-based control. With \( SP_{\text{min}} \) and \( SP_{\text{max}} \) denoted as minimum and maximum SP during the next 24 hours, low (LPT) and high (HPT) price thresholds were defined via (3) and (4), respectively. Thresholds were chosen to limit the number of low/high price hours. The related temperature setpoints are shown in Table 3 and on average, 25 %, 60 % and 15 % of the time low, medium and high prices occurred, respectively. During low prices, higher DHW setpoints are feasible, but as only the BUH is then allowed, efficiency decreases. Hence, the upper temperature limit remains. During high SP, the lower limit is slightly decreased to ensure end-user comfort. SH temperature setpoints are increased during low SP, while being slightly reduced during high SP to keep end-user comfort.

Case 4 and 12 are chosen for flexible control and further denoted as case 13 and 14, respectively. Case 4 is chosen as such HP models are regularly used for flexible control and case 12 shows the most accurate model of this paper.

Table 3: Temperature setpoints depending on spot price

<table>
<thead>
<tr>
<th></th>
<th>Low price</th>
<th>Medium price</th>
<th>High price</th>
</tr>
</thead>
<tbody>
<tr>
<td>DHW lower limit (°C)</td>
<td>50</td>
<td>45</td>
<td>42.5</td>
</tr>
<tr>
<td>DHW upper limit (°C)</td>
<td>55</td>
<td>55</td>
<td>45</td>
</tr>
<tr>
<td>SH lower limit (°C)</td>
<td>20.5</td>
<td>19.5</td>
<td>19.25</td>
</tr>
<tr>
<td>SH higher limit (°C)</td>
<td>21</td>
<td>20.5</td>
<td>19.75</td>
</tr>
</tbody>
</table>

\[
LPT = SP_{\text{min}} + 0.20 \cdot (SP_{\text{max}} - SP_{\text{min}}) \tag{3}
\]
\[
HPT = SP_{\text{min}} + 0.85 \cdot (SP_{\text{max}} - SP_{\text{min}}) \tag{4}
\]

Results

This section presents the results, in which the influence of internal control is firstly discussed via yearly results in Table 4, a typical day and short-term figures. Secondly, the flexible control strategy with spot prices is analysed. As results for both parts will indicate, most differences could be seen on the short-term behaviour. Long-term influences on the overall energy consumption or SCOP are rather small. Hence, results are mainly discussed via short-term figures.

Part-load data and environmental heat losses

Case 1 and 2 provide that inclusion of the condenser heat losses, decreases the Seasonal Coefficient of Performance (SCOP). As the BUH is only used for DHW, thus providing high temperatures, the influence on its energy consumption can be clearly seen. As heat losses always occur, more energy is consumed. In this study, the evaporator is supplied with a constant temperature of 10 °C and hence, environmental heat exchanges for the evaporator are not considered. Usage of part-load data increased the SCOP, while the compressor consumption decreased, and due to constant efficiency no effect for the BUH could be seen. Modulation rates slightly changed as the part-load heating capacity is not perfectly linear with the full-load data. For case 1-3, no minimum modulation was used. Inclusion of heat losses caused a compressor cycles decrease as the HP keeps the water at temperature, even if no heat is needed and HP on-times thus increased.

Figure 5 shows the compressor and BUH power during a typical day, and displays profile agreement for case 1-3. Differences at DHW cycle endings could be seen for case 1, in which the BUH delivered a higher useful power and shortened the cycle. As the part-load COP is frequently higher, lower compressor powers occur in case 3. Some inhabitants took a bath in the morning, while the DHW tank was at 46 °C and hence, two DHW cycles occurred.

Modulation and timing constraints of compressor and BUH

Figure 6 displays compressor and BUH power during a typical day. Modulation limits increase the SCOP and...
When the tank reaches the minimum compressor off-time in 5 s as after DHW cycles, outlet temperatures are too high. The minimum compressor modulation causes higher compressor power, lower BUH power and higher outlet temperatures.

In addition, condenser heat losses cause regular HP cycles as the HP power is too high. The influence of on/off-times on the overall performance seems negligible, however, it should be noted that a 20 l-tank for inertia requirements is already foreseen. If no heat is required during minimum on-times, temperatures rise and if heat is required during minimum off-times, water temperatures decrease. Temperature volatilities are thus introduced and the 20 l-tank regularly creates more inertia than needed. Figure 7 shows that after DHW cycles, low return temperatures occur and that the minimum off-timer prevents too short compressor cycles. DHW timing constraints and, coordination of compressor and BUH working areas, show a SCOP and compressor consumption increase, while BUH consumption reduced with 23.95 %. Previously, the BUH directly supported DHW cycles. At start, the compressor cannot directly reach 55 °C and the BUH was assisting, while from case 6, only the compressor is used. When the tank reaches 53 °C, the compressor stops and only the BUH is used. As such, the usage of the BUH is limited, but DHW cycles are frequently not completed within 60 minutes, while the compressor is already off due to its off-setpoint of 53 °C tank temperature. After 30 minutes in SH, the DHW cycle restarts, but differently. If no DHW is consumed, the tank is still above 53 °C, so only the BUH will work, while its power is limited to only 3 kW. Therefore, DHW cycles are longer and differences can be seen between the number of DHW requests from the tank thermostat and the number of three-way valve switches. Due to longer cycles, the tank remains longer at high temperatures and therefore, standing losses increase while DHW thermostat cycles decrease. With longer DHW cycles and less high power, the SCR increases. In addition, BUH control shows differences at DHW cycle ending. Previously, the BUH outlet raised until 57 °C and remained constant afterwards, while the BUH controller uses a 1 °C hysteresis before a 1 kW reduction. Although a limited long-term impact, the BUH frequently supplies higher temperatures and occasionally a single reheat is feasible.

**Table 4: Performance influence of internal control strategies (yearly results)**

<table>
<thead>
<tr>
<th>Case</th>
<th>SCOP</th>
<th>Compressor consumption [kWh]</th>
<th>BUH consumption [kWh]</th>
<th>Compressor cycles</th>
<th>Average modulation [%]</th>
<th>Average compressor run-time [min]</th>
<th>Average pump run-time [min]</th>
<th>Total thermostat cycles</th>
<th>Three-way valve position switches</th>
<th>Self-consumption (SCR) [%]</th>
<th>Self-sufficiency (SSR) [%]</th>
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<tbody>
<tr>
<td>1</td>
<td>5.26</td>
<td>3485</td>
<td>814</td>
<td>639</td>
<td>45.92</td>
<td>418</td>
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<td>0.318</td>
<td>638</td>
<td>563</td>
<td>446</td>
<td>30.18</td>
</tr>
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</table>
Inertia systems such as underfloor heating are slower and thus less critical. Figure 10 shows a detailed DHW cycle. As previously discussed, 60 minutes are frequently not enough to reheat the DHW tank as 75–85% of this time is used to reach a tank temperature of 53 °C and afterwards, the heating power significantly drops as only the BUH can then be used. Lowering the DHW on-time thus causes many small cycles in which the tank is only slightly heated. When a switch from compressor to BUH occurs, during the next on-time, the BUH can reheat the condenser from SH temperatures to 57 °C, while its power is limited to 3 kW and after 30 minutes, the DHW cycle goes off and part of the BUH power is recovered for SH purposes. If no SH is requested, the bypass valve is used, the water will drop less in temperature and during the next DHW cycle, the BUH can reach its setpoint temperature earlier and the tank can sooner reach the setpoint of 55 °C. Changes in BUH consumption and SCOP clearly indicate the impact, while changes can also be seen in SH. After the first 30 minutes, the compressor is still on as tank temperatures are still below 53 °C. As the controller detects too high HP outlet temperatures when switching to SH, it performs an on/off cycle and the compressor is off for its minimum off-time and thus not available for SH, while a next DHW cycle occurs after only 30 minutes. SCR increases as DHW cycles are longer and more BUH energy is used, while the number of DHW cycles drops and a better match with the DHW draw-off profile occurs. In contrast, as DHW cycles last for only 30 minutes, the three-way valve frequently switches from position.

Case 11 considers a weather dependent DHW on-time and based on the average yearly temperature, the maximum DHW on-time is 94 minutes, while analysis shows that in most cases 60-70 minutes are sufficient enough. Most DHW cycles can then thus be accomplished in a single cycle. Therefore, the BUH can directly start after the compressor, should not heat up the heating water from the previous SH cycle and the system works more efficient. During cold days, the DHW on-time is limited to ensure end-user comfort in both SH and DHW and, causes more HP and three-way valve cycles. During these high temperatures and hence, it takes longer to reach the HP outlet setpoint during DHW. Figure 9 shows that at DHW cycle start, the compressor has a higher inlet temperature compared to case 8. Hence, DHW cycles can occasionally be accomplished within 60 minutes and a next cycle with only the BUH can be avoided. During SH, the pump control frequently provides higher flow rates and therefore, rooms warm up quicker, more room thermostat cycles occur, the bypass valve is frequently used and more HP cycles occur. With an active bypass, the requested power is low. In previous constant flow rate cases, the 20 l-tank was heated with high flow rates, while with a variable speed pump and active bypass, the pump reduces its flow rate as it could not detect a sufficient temperature difference. It could be seen that the 20 l-tank is 0.5 – 1 °C less heated compared to a constant flow pump.

DHW timing constraints

Case 10 keeps a maximum DHW on-time of 30 minutes to ensure SH comfort in low-inertia heating systems. High inertia systems such as underfloor heating are slower and thus less critical. Figure 10 shows a detailed DHW cycle. As previously discussed, 60 minutes are frequently not enough to reheat the DHW tank as 75–85% of this time is used to reach a tank temperature of 53 °C and afterwards, the heating power significantly drops as only the BUH can then be used. Lowering the DHW on-time thus causes many small cycles in which the tank is only slightly heated. When a switch from compressor to BUH occurs, during the next on-time, the BUH can reheat the condenser from SH temperatures to 57 °C, while its power is limited to 3 kW and after 30 minutes, the DHW cycle goes off and part of the BUH power is recovered for SH purposes. If no SH is requested, the bypass valve is used, the water will drop less in temperature and during the next DHW cycle, the BUH can reach its setpoint temperature earlier and the tank can sooner reach the setpoint of 55 °C. Changes in BUH consumption and SCOP clearly indicate the impact, while changes can also be seen in SH. After the first 30 minutes, the compressor is still on as tank temperatures are still below 53 °C. As the controller detects too high HP outlet temperatures when switching to SH, it performs an on/off cycle and the compressor is off for its minimum off-time and thus not available for SH, while a next DHW cycle occurs after only 30 minutes. SCR increases as DHW cycles are longer and more BUH energy is used, while the number of DHW cycles drops and a better match with the DHW draw-off profile occurs. In contrast, as DHW cycles last for only 30 minutes, the three-way valve frequently switches from position.

Pump control

Case 8 shows decreasing average room temperatures as the condenser pump detects small temperature differences between HP inlet and outlet, it reduces its flow rate and frequently to the minimum during SH. Although weather dependent control reduces SH supply temperatures, the controller keeps 5 °C temperature difference and causes lower mean water temperatures and lower underwater heating radiation. Therefore, the HP supplies more frequently useful heat for SH instead of using the bypass valve. As the flow rate is regularly reduced more than the temperature difference increases, lower modulation rates occur. Although these effects seem positive, the average room temperatures drop below 20 °C and user comfort is affected. SCR and SSR increase as the HP provides a more continuous operation. In contrast, DHW cycles are slightly faster for two reasons. Firstly, at cycle start, return temperatures are low, the pump speed increases and hence, the average water temperature increases. Secondly, at DHW cycle ending, return water gets warm, the flow rate decreases which gives more time to supply heat to the tank and lower flow rates cause the BUH to faster reach its setpoint temperature. Although negligible, lower flow rates cause less stored heat in the lower tank layers. Figure 8 shows the power profiles for a typical day for case 8-12. Case 9 shows a significant decrease in BUH consumption. Comparison of case 8 and 9 indicates that maintaining a 5 °C temperature difference in SH, gives lower HP inlet
switching moments, average room temperatures slightly decrease as the HP has less time for SH as previously indicated in case 10. As these days do not occur much, the impact remains limited. The limited number of three-way valve switches, causes less time of high SH supply temperatures directly after a DHW cycle and causes less room temperature variations and room thermostat cycles.

Figure 10: Detailed view of DHW cycles in case 10

Case 12 shows the effect of anti-legionella cycles in which during cold periods, differences are noticed as for these cycles 125 minutes DHW on-times are possible. In case these cycles are neglected, lower DHW on-times occur and tank reheating cannot be accomplished within a single cycle. In those cases, heating the tank until 60 °C for anti-legionella, causes higher standing losses and lower energy efficiency, but less DHW cycles occur as 125 minutes are sufficient enough to heat the tank in a single cycle. As anti-legionella cycles only occur every Sunday, small differences could be expected, although Table 4 indicates differences between case 11 and 12 for the SCOP, DHW cycles and energy consumption of both the compressor and BUH. As anti-legionella cycles occur during night hours, the SCR and SSR are neglected.

Profile agreement for case 1-11 compared to case 12

Figure 11 shows profile agreement of case 1-11 with case 12 as the latter is closest to the real HP. The curves can be seen as duration curves as for each minute of the year, the electrical HP power of one case is compared to case 12. If within a certain percentage (e.g. +/- 10 % of case 12), a counter is increased and at the program ending the counter is divided by the number of time steps. Depending on the case, 42 – 56 % of the year, the deviation was within +/- 10 % of the HP power of case 12. Hence, it could be stated that the more the internal control is modelled, the better the agreement gets, except for cases 8 and 10. Case 8 used a 5 °C temperature difference pump control and lowered room comfort, while case 10 considered a maximum DHW on-time of 30 minutes and caused many three-way valve switches as DHW cycles generally lasted more than 60 minutes. Compared to case 1, case 2-3 show less profile agreement. As heat losses always occur and no further on/off control is considered, the HP is generally on. Hence, the power deviates from case 12 as in the latter on/off control with minimum on/off-times is considered. In contrast with a visible impact of case 4 & 6 when compared to previous cases, cases 5 & 7 only show small changes as minimum on/off-times and discretised BUH control impact remains small. In contrast, pump control, weather dependent DHW on-time, and anti-legionella cycles showed remarkable impact. As the internal control modifies the HP operation, curves almost vertically rise at yearly percentages of 90 %.

Figure 11: Profile agreement of case 1-11 with case 12

Table 5: Influence of HP modelling during spot prices and without/with flexible control (case 4 & 12/13 & 14)

<table>
<thead>
<tr>
<th>Case</th>
<th>Load cost without PV (€/year)</th>
<th>Load energy without PV (kWh/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>458.78</td>
<td>8179</td>
</tr>
<tr>
<td>12</td>
<td>446.10</td>
<td>7989</td>
</tr>
<tr>
<td>13</td>
<td>445.10</td>
<td>8251</td>
</tr>
<tr>
<td>14</td>
<td>431.41</td>
<td>8061</td>
</tr>
</tbody>
</table>

Influence of HP modelling during flexibility

Table 5 shows the yearly energy consumption and cost for cases 4, 12, 13 and 14 if a spot price would be used. Using a more accurate HP model without flexible control already decreases the energy consumption (-2.33 %) and load cost (-2.76 %). Given percentages consider the total load (sum of HP and general electricity consumption, but without PV). As the cost in case 12 reduced more than the consumption when compared to case 4, it could be stated that the advanced model already better matches with the needs of the electricity grid and that the ability of the HP for flexibility purposes is thus expected to be lower. In contrast, results show that the advanced model with flexible control (case 14) could reduce its annual cost even more when compared to case 13. Furthermore, the provision of flexibility increased the energy consumption of both models with the same amount of energy. Hence, it could be stated that the HP model influences its operational behaviour, but that energy losses due to flexible control remain constant. Figure 12 shows DHW and SH behaviour during seven days with flexible control. Anti-legionella cycles, DHW timing constraints and no series operation of BUH and compressor time-shift DHW cycles. During anti-legionella cycles, no flexibility could be provided, while it could be seen that after a few days, DHW cycles will again match better as the DHW draw-off profile and dynamic prices will force the operation into a similar schedule. However, DHW cycles are longer in case 14 and cause different effects. During short periods of low prices, the DHW tank is less charged, while during long periods of low prices, advantage could be taken if prices drop further. During DHW cycles, room...
temperatures drop, but the condenser pump control influences the recovery rate of SH room temperatures. As the pump controller in case 14 provides higher flow rates compared to a constant flow rate as in case 13, the average water temperature increases and more radiation effect from the underfloor heating occurs. Although a faster recovery, the effect on SH temperatures remains small. Lastly, Table 4 shows non-negligible differences for cases 13 and 14 which are mainly caused by the DHW cycles.

Figure 12: Flexibility: HP model influence on SH/DHW

Conclusion

This paper investigates the modelling influence of internal control strategies for a water-to-water heat pump. Starting from a basic performance data model without any internal control strategy, control blocks are gradually added. Both short- and long-term effects are investigated and non-negligible effects are noticed. Analysis shows that most impact can be seen in the provision of domestic hot water and is caused by different control blocks. As in this study, space heating occurs via underfloor heating, which typically has high thermal inertia, influences in room comfort are rather small, although simulations showed the importance of an adequate control. Comparison showed that for 42 – 86 % of the year, the electrical heat pump power of the simplified models was within +/- 10 % of the most detailed model and power profile modification occurred. Moreover, a predictive rule-based control was used to adapt the heat pump operation to the needs of the electricity grid. A simplified heat pump model which is generally used for flexibility testing was compared with a model which includes the internal control. Short- and long-term analysis again showed that constraints on minimum modulation, minimum on/off-times, domestic hot water timing, condenser pump control and even anti-legionella cycles clearly influenced the heat pump ability to perform flexible behaviour. Hence, the relevance of modelling these internal strategies, especially on short-term behaviour, is shown. This was the preliminary work for future tests and validations in a HIL infrastructure.

References


Daikin. (2020). Daikin geothermal HP EGSA06D9W.


