Quantifying the effect of radiator capacity on hybrid heat pump performance using a hardware-in-the-loop setup

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Abstract

Heat pumps achieve higher efficiency (COP) if the water temperature at which they reject heat is lower. A method to lower this temperature is by increasing the capacity of the hydronic heating system. A larger heating system can deliver the same amount of heat at a lower water temperature compared to a smaller system. However, the relationship between heating capacity and COP varies depending on the system. To quantify this for a hybrid air-to-water heat pump, a hardware-in-the-loop method was employed. The heat pump was tested in a climate chamber, connected to a virtual house and hydronic radiator heating system. Tests were repeated with upgraded radiators (from Type 22 to Type 33) and finally with a revised weather compensation curve. The case study demonstrated that the increased radiator capacity and adjusted weather compensation curve resulted in a COP increase of approx. 0.4 (approx. 10%).

Keywords: (hybrid) heat pump, hardware-in-the-loop (HIL), COP, hydronic radiator, weather compensation curve, emulator

1. Introduction

The relationship between heat pump supply water temperature and radiator capacity is a fundamental aspect of heating systems. Understanding the complexity between these two parameters is essential for optimising heating system performance, achieving thermal comfort, and minimising energy consumption. It is generally known that with larger radiators, the heat pump can operate at a lower water temperature while maintaining the desired indoor temperature. This increases the heat pump's efficiency, potentially leading to lower energy consumption and reduced operating costs.

The hybrid air-to-water heat pump, a system that combines a conventional heat pump with an (existing) gas boiler, offers an effective retrofit solution for homes in the Netherlands, where most households are already equipped with gas boilers. This study therefore focuses on hybrid air-to-water heat pumps and examines the impact of radiator capacity on their performance. Testing was conducted at TNO’s Heat Pump Application Centre (HPAC) in the Netherlands, where actual water-based hardware, such as air-to-water heat pumps, can be tested in a simulated outdoor environment, paired with a fully dynamic house model, including a heating system. This approach combines the modeled load with actual hardware, providing better insights into how a hybrid heat pump performs under real-world conditions compared to static testing methods or purely model-based approaches - especially when interactions are complex to model.

In addition to providing more realistic system dynamics, the setup is well-suited for parametric measurements which enable the investigation of the radiator capacity effect under the same conditions - this is normally very challenging with standard field measurements in practice. Consequently, this paper explains how this setup, called hardware-in-the-loop (HIL), uses these parametric studies to quantify the impact of radiator capacity on hybrid heat pump performance.

2. Method

As part of a government-funded research program in the Netherlands, the performance of hybrid heat pumps is measured in a hardware-in-the-loop (HIL) setup. The general idea of the HIL is that the tested (hybrid) heat pump does not ‘know’ that it is in a test environment. This is achieved by bilaterally coupling the (hybrid) heat pump to a house model with a heating system running in real-time. The general structure of the HIL is shown schematically in Figure 1. The interaction between the hardware and software is represented by dashed lines.

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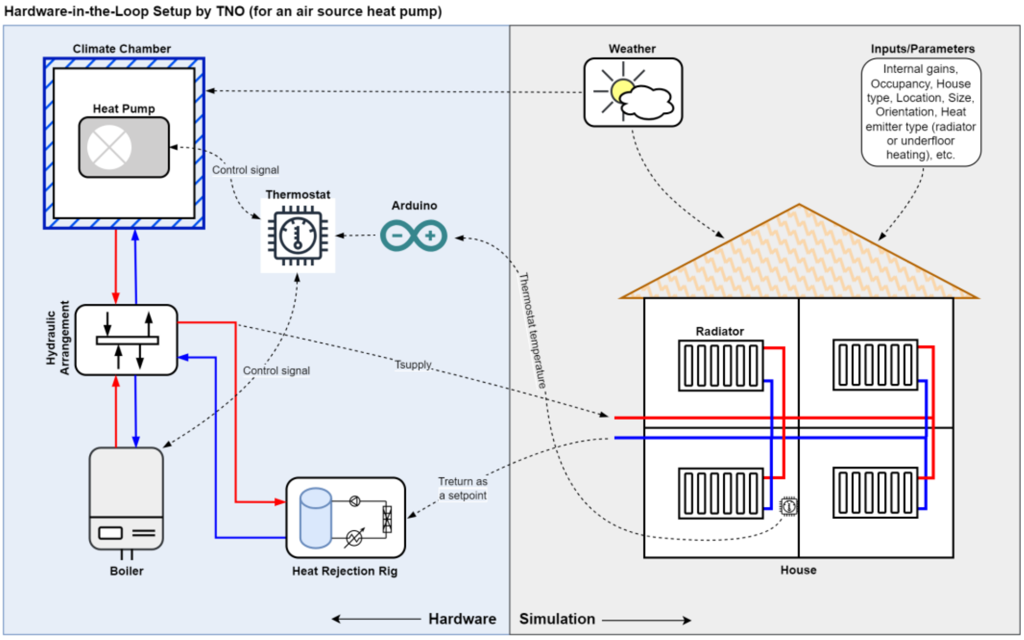

Fig. 1: Description of test setup. Left: hardware environment with climate chamber, heat rejection rig and thermostat. Right: software environment with house, radiators and weather scenario. Dashed lines are data connections.

The typical operation of the HIL setup is as follows: The climate chamber provides time-dependent ambient conditions, i.e. temperature and humidity, based on a predefined reference weather profile. The heat pump operates according to its internal control logic. The generated heat is then transferred to the heat emitter model (e.g. radiator or underfloor heating) in the house model. The room thermostat and heating system water temperatures are calculated based on the dynamic heat balance equation in the models. The calculated return water temperature is sent to the heat rejection rig as a setpoint so the heat pump. Finally, the heat rejection rig conditions the water and sends it to the heat pump back.

2.1. House model

A dynamic multi-zone house model was developed using the Type 56 within TRNSYS 18 (Klein, 2017), representing a terraced Dutch housing typology of the late 1980s to early 1990s. These houses typically have three floors. The ground floor includes the living room, kitchen, and entrance. The first floor comprises the bathroom, hallway, and all three bedrooms. The top floor is attic space, assumed to be unheated. The useful area, excluding the attic, is 109 m² (SenterNovem, 2007). Each space in the house was defined as a thermal zone, leading to a total of 9 zones.

Typical thermal resistance properties (Rc/U values) of this housing typology were obtained from (Agentschap NL, 2011). To accurately model the thermal mass, specific attention was paid to determine the typical construction details of the building envelope, interior walls and floors, but also the presence of furniture. Additionally, an advanced ventilation model was integrated into the house model using TRNFlow in TRNSYS 18 (Transsolar Energietechniek GmbH, 2009). TRNFlow allows modelling air exchange through the building envelope and between thermal zones, considering driving forces such as wind pressure and buoyancy. Only natural ventilation is present in the house model. Therefore, air is primarily supplied via ventilation grilles and extracted by passive exhaust ducts in the kitchen, bathroom, and toilet, according to the requirements from the Dutch Building Code (Nederlands Normalisatie Instituut, 1975; 2001). Infiltration was also implemented into TRNFlow based on a qv;10 value (the infiltration flow at a pressure differential between inside and outside of 10 Pa) of 222 dm3/s based on NTA 8800 (Nederlands Normalisatie Instituut, 2019) and it was distributed over the building envelope based on (Vereniging Leveranciers Luchttechnische Apparaten, 2019).

The main sources of internal heat gain are occupancy, appliances, and lighting. For occupancy, a two-person household with one child was assumed. Occupancy profiles per person per room were obtained from (Vereniging Leveranciers Luchttechnische Apparaten, 2019) and the same daily profile was iterated in the simulation. In order to incorporate the heat gain released by the appliance and lighting, the yearly electricity consumption of approx. 3300 kWh was assumed. The daily appliance and lighting schedules were created based on the defined occupancy profile and the monitored cases of multi-occupancy houses with a child (Zimmermann et al., 2012). Not all electrical use was assumed to result in room heating, for example, a washing machine and dishwasher use a significant amount of electricity, rejecting most of the heat via the sink.

The nominal heat load (peak load) of 6 kW was calculated under design conditions (an ambient temperature of -10°C, a wind speed of 5 m/s, and no solar or internal gains) for this house. The annual heat demand for space heating was estimated to be between 7.3 and 7.9 MWh, which is equivalent to Label B, based on the CBS gas consumption data (Centraal Bureau voor de Statistiek, 2021).

2.2. Radiator model

The modelled house is heated using only radiators as heat emitters. Since the radiators are coupled to the (hybrid) heat pump, their behaviour is crucial for the system's performance. Each radiator in the house is modelled separately and coupled to the house model. The model follows the EN442 standard (Nederlands Normalisatie Instituut, 2014) for characterizing radiator thermal performance, with added thermal inertia to capture dynamic responses. Validation of the model was carried out against extensive measurements conducted on panel radiators.

Thermal output and heat pump defrosting

If an air source heat pump defrosts via a reverse cycle, heat is removed from the radiator circuit. In practice, this means that the water inlet temperature of the radiator drops below the water outlet temperature. Radiators do not work optimally if the hot water inlet is connected to the bottom and the cold water outlet is connected to the top. The buo yancy of the water normally stratifies the internal volume with the hot water at the top. Temporarily reversing the connections thus short-cuts the radiator. This results in only a small fraction of the thermal inertia of the water being used and the temperature at the water outlet of the radiator drops much faster than is expected based on the full radiator volume. The effect of this shortcutting can be seen in Figure 2, by a drop in temperature of the radiator body on the connection side during the defrost. After the defrost the temperature recovers again and the stratification resumes. This phenomenon was integrated into the radiator model and validated through extensive testing.

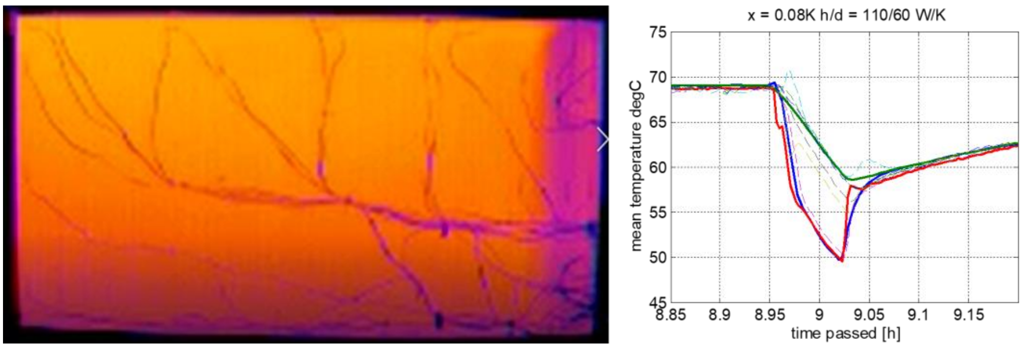

Fig. 2: Left: Thermal image of a panel radiator during a heat pump defrost (reverse) cycle. The hydronic connections are on the right side. The purplish (colder) area on the right side indicates shortcutting of water flow. The black veins' are thermocouple wires. Right: The graph displays the results of the radiator model with and without defrost logic. The red line shows the measured mean inlet and outlet temperatures of the radiator, compared with the model results: with defrost logic (blue) and without defrost logic (green).

Thermostatic radiator valves

Thermostatic radiator valves (TRVs) are a common means of controlling room temperatures outside the zone containing the main heating system thermostat. Therefore, it was assumed in the modelled house that each room radiator (except for the living room) is equipped with a TRV. In the model, TRV setpoints of 20°C for the kitchen, 22°C for the bathroom, and 18°C for the bedrooms, hallway, and entrance were used. These values are based on ISSO 51 (ISSO Kennisinstituut voor de Installatiesector, 2009).

The TRV model was created based on EN215 (Nederlands Normalisatie Instituut, 2014) including the physics of the measuring body's time constant, valve hysteresis and the effect of water temperature on the sensed temperature of the body. It senses the room air temperature and adjusts the valve with proportional control. The model then calculates water flow resistance for the heating system circulation pump and allocates flow distribution between radiators. In the tested heat pump this effect is achieved by adjusting a calibrated flow control valve in the heat rejection rig, ensuring the connected hybrid heat pump experiences the same flow resistance as the modelled heating system.

2.3. Heat rejection rig

The heat generated in the form of warm water is typically delivered to a heating circuit in the house, such as radiators or underfloor heating. To emulate this connection, a purpose-built rig is used. This rig adjusts the temperature of the return water to the heat generator by means of cooling or heating. This way the entering water temperature of the physical heat pump is equal to the temperature calculated by the computer model of the heating circuit. Additionally, the hydraulic resistance of the heat rejection rig is controlled using a motorized valve to mimic the variation caused by thermostatic radiator valves in the model.

2.4. Hybrid heat pump

The HIL tests were conducted using a commercially available hybrid heat pump, selected by the manufacturer as a suitable match for the modelled house described in Section 2.1. The thermal specifications of the unit based on the manufacturer's catalogue are presented in Table 1.

Tab. 1: Thermal specifications of the unit based on the manufacturer's catalogue

HP thermal capacity [kW]	5.5	at 2 °C ambient and 35°C leaving water
HP thermal capacity [kW]	4.8	at -10 °C ambient and 35°C leaving water
HP SCOP [-]	3.3	with 55 °C leaving water temperature for an average climate
Boiler thermal capacity [kW]	25	at 80 °C leaving and 60 °C return water temperatures

The unit was hydraulically connected in accordance with the manufacturer's recommendations for the modelled house type. As shown in Figure 3, the air-to-water heat pump is located in the laboratory's climate chamber and all indoor parts of the hybrid (gas boiler, indoor unit, etc.) are located in the general lab area. The indoor unit contains a header, mixing valve, and circulation pump, enabling controlled mixing of the gas boiler and heat pump circuits (note that the header and mixing valve are not drawn in Figure 3).

The tested unit offers several configuration settings to tune system performance, such as the weather compensation curve[1], the switch-over point[2] between the heat pump and boiler, and room thermostat compensation[3]. For these settings, the manufacturer's recommendations for the selected house type were followed to mimic the unit's performance in a real-world application. Additionally, the living room thermostat was set at 20 °C without a night setback.

[1] It is the process of adjusting the heating water temperature with the outdoor temperature. It is typically set via selection of pre-set curves, or by manual definition of the line. In the Netherlands, the maximum heating water temperature of the curve is set at -10°C ambient temperature (design condition).
[2] It is a function for blocking the boiler and heat pump operation with respect to outdoor temperatures and/or COP threshold (e.g., the boiler does not operate above x°C and the heat pump does not operate below y°C, or heat pump does not operate below certain COP).
[3] It is about how the room thermostat temperature influences the target water temperature. Some units include functions that adjusts the target water temperature based on room temperature. However, it was not always clear what the function is doing. Some of these settings include numerical input values, others include an option to switch on/off a feature or to select a correction method via a choice of correction type.

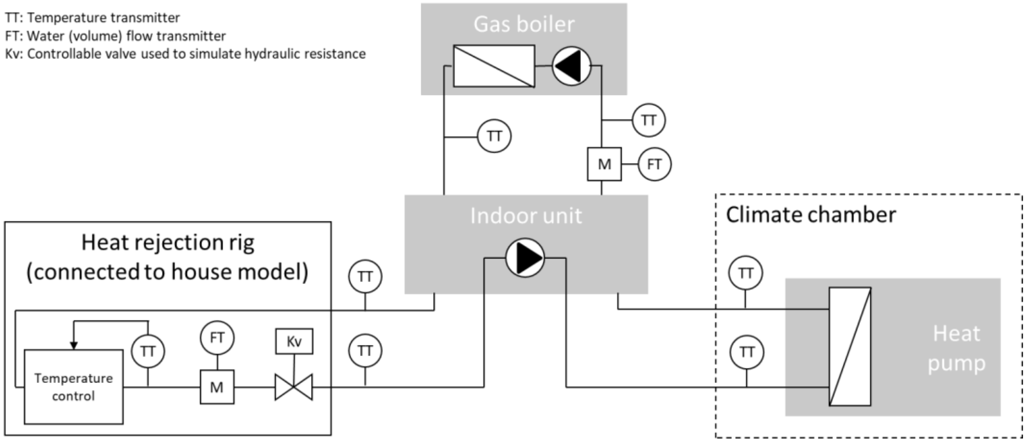

Fig. 3: Hydraulic configuration of the test setup

It should be emphasized that there was no additional information regarding the systems' control other than that available from the product manual because there was no interaction with the product design engineers or software programmers during the project, therefore, the control logic of the unit was essentially black box. In the following sections, some commentary is therefore made regarding notable operational characteristics of the unit.

2.5. Interface with the room thermostat

The heat pump controller usually uses the room thermostat temperature as a control feedback. To ensure proper operation of the system, the thermostat should read the correct room temperature. In the HIL setup, the real reference sensor is removed and replaced by a virtual sensor, which emulates a temperature coming from the house model at the assumed thermostat location.

2.6. Data acquisition

The setup was extensively instrumented with calibrated instruments, as illustrated in Figure 3. Data acquisition was performed using in-house data acquisition software and hardware, with a sampling interval of 10 seconds. On the hydraulic side, water temperatures at the inlet and outlet of each heating system component were measured, along with all water flow rates. On the air side of the heat pump, sensors for air temperature (in and out) and relative humidity were installed. Additionally, electrical power is measured individually for each component of the hybrid (heat pump, gas boiler and indoor unit) as well as boiler gas consumption. The flow measurement combined with calculated density and the temperature difference across different components is used to calculate generated or absorbed heat. These instruments combined provide full information on the energy balance of each component.

2.7. Reference weather days

As the HIL tests are conducted in real-time, it is impractical and undesirable to extend the testing period excessively. Therefore, six reference days (-5, -1, 2, 4, 7, and 12-degree days) were derived from NEN5060 (Nederlands Normalisatie Instituut, 2008). These days are selected to cover a range of average daily temperatures throughout the heating season, ensuring that the conclusions are applicable across the entire period.

The reference year was sorted into days with the same daily average dry bulb temperature when rounded as an integer (referred to as temperature bins in various sources). Taking the average hourly temperatures of the days within the integer bins results in a somewhat flattened temperature profile so the difference between the hourly values and the daily average was scaled (increased) to match the median standard deviation of the days within the bin. The relative humidity (RH) of all hours in the year was correlated with the dry bulb temperature. Using this correlation, hourly values of RH were assigned according to dry bulb temperature in the weather files of the 6 reference days. A solar radiation profile per average temperature day was needed, so using the same bin method as for dry bulb temperature the average solar radiation per hour was used for each reference test day.

2.8. Preconditioning and an actual test day

Since the test days are analogous to “snapshot” days in a heating season, it is important to precondition the house model with similar weather days. This ensures that the various construction elements reach appropriate temperatures at the start of the actual HIL test, thereby minimising the thermal buffering effect. This was achieved by running a preconditioning period of house and heating system simulation for 4 simulation days[1] with a looped reference weather day before the actual HIL became operational, as illustrated in Figure 4. For this period, a fictitious and simplified heat generator and a control were included.

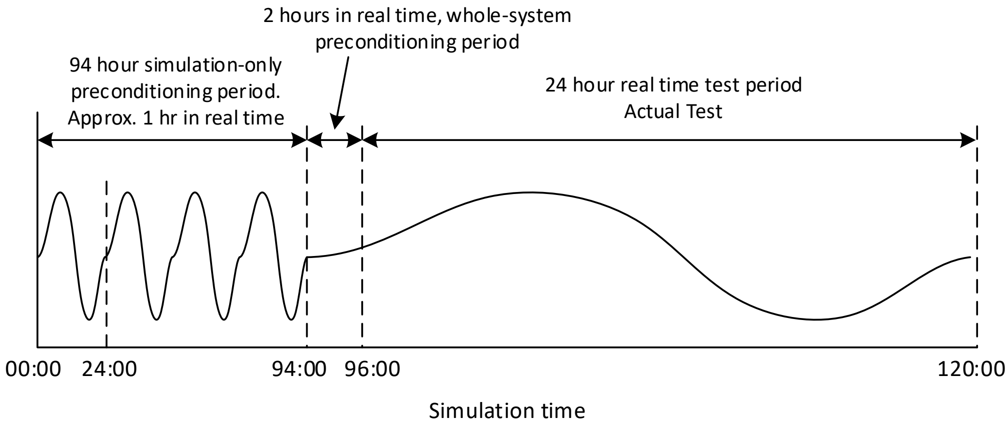

Figure 4: Arrangement of preconditioning and actual test day

This period was followed by the actual HIL for a simulated time from 94:00 to 96:00, allowing for some preconditioning time for the hardware (e.g., heat pump, boiler, heat pump controller, and heat rejection rig) as well. Finally, the actual test ran for a 24-hour period, beginning at 96:00 simulation time, which corresponds to 00:00 clock time at the start of the test day, as illustrated in Figure 4.

3. Parametric study: Radiator capacity

The HIL setup is not only useful for obtaining more realistic system dynamics but also quite suitable for parametric measurements in which the radiator capacity effect can be investigated purely while other factors remain the same. However, this is very challenging with standard field measurements in practice. In the HIL setup, there is full control over the model and the parameters can be adjusted easily. Simply said, the setup allows us to install larger radiators in the modelled house without any plumbing work.

Using this advantage of the setup, three test cases were defined, as shown in Table 1. While the hybrid heat pump and the house model remained the same, the radiator capacity and the weather compensation curve were varied. The initial case (Case 0) was conducted as a baseline scenario with the original radiator capacity of 9 kW at 75/65/20°C[2] and a maximum water temperature of 55°C[3] on the weather compensation curve at an outdoor temperature of -10°C. All radiators were assumed Type 22 which is with 2 plates and 2 convectors. Then, in Case 1, while keeping the dimensions (length and height) the same, the radiators were upgraded from Type 22 to Type 33 (3 plates and 3 convectors) which brings approximately a 50% capacity increase (Radson, 2020). During this case, the weather compensation curve was kept the same as the base case. Upgrading the

[1] The number of days depends on house type (heavy/lightweight) and other conditions such as night setback, heated/unheated attic, etc. Therefore, each house model used in the HIL setup needs to be analysed carefully before starting the test.

[2] It is the typical Dutch radiator design condition, representing the radiator inlet, outlet and room temperatures respectively.

[3] The weather compensation curve was set by the installer according to standard practices for the similar type of houses.

radiators could be done with underfloor heating, low-temperature convector, radiator booster fan, etc. However, the purpose of the article is not to do a techno-economic analysis on retrofitting the heating emitters, but rather to show the impact of the radiator capacity on the (hybrid) heat pump performance. Finally, the maximum water temperature of the weather compensation curve was reduced to 50°C in Case 2 while keeping the radiator capacity the same as in Case 1.

Tab. 1: Cases for the parametric study

Parameters	Case 0	Case 1	Case 2
Radiator	Type 22 9 kW nominal capacity at 75/65/20°C	Type 33 13.6 kW nominal capacity at 75/65/20°C	Type 33 13.6 kW nominal capacity at 75/65/20°C
Weather compensation curve	Maximum water temperature of 55°C at an outdoor temperature of -10°C	Maximum water temperature of 55°C at an outdoor temperature of -10°C	Maximum water temperature of 50°C at an outdoor temperature of -10°C

An important factor in this study is the original design capacity of the radiator: non-representative estimations may lead to misleading conclusions. Defining a realistic installed radiator capacity, however, is challenging due to a lack of availability of past building regulations[1] for existing Dutch buildings. There are reasons to expect radiators to be oversized, for example, related to design safety margins, allowances for intermittency and risk aversion with respect to underheating. Therefore, to estimate the radiator capacity in the modelled house, a sizing factor of 1.5 was applied to the nominal heat load (6 kW) of the house under design conditions (an ambient temperature of -10°C, a wind speed of 5 m/s, and no solar or internal gains). This is equivalent to a nominal capacity of 9 kW at 75/65/20°C.

A recent field measurement done with a representative dwelling sample[2] concludes that 80% of existing radiator systems can provide the required heating at the nominal condition with a supply temperature of 60°C and is largely independent of building type, construction period or specific annual heat demand (Pothof et al, 2022; 2023). Note that the study presumably includes some houses that have been renovated with heat loss reduction measures. This will also make the radiators "oversized", but doesn't mean the original system was, or at least not by as much as the analysis might suggest. Nevertheless, the sizing factor is considered to be a reasonable sizing estimate but is still subject to some uncertainty.

4. Test results

All cases defined in the previous section were tested in the HIL setup over 3 reference weather days with average ambient temperatures of -1, 2 and 4°C. These days account for a significant part of the heating season in the Dutch climate (Nederlands Normalisatie Instituut, 2008). This section will present some observed results of the parametric study as well as the control characteristics of the unit.

4.1. Control characteristics of the unit

The setup allows for highly detailed monitoring of the performance of the tested unit. Figure 5 illustrates the measurements of temperature (thermostat, supply, and return temperatures), flowrate (main circuit and boiler circuit), and power (thermal and electrical) for Case 0 on a reference weather day of 4°C. Also, the weather compensation curve is shown in the figure and it was calculated based on a linear correlation, which slightly differs from the unit's set curve but still serves as a good indicator.

When the unit switches on, it controls in such a way that the heat pump leaving water temperature targets the temperature calculated from the weather compensation curve (Figure 5, plot 2). Initially, it requires a high

[1] The first known regulation on this topic was ISSO51 (ISSO Kennisinstituut voor de Installatiesector, 2009).
[2] A sample of 187 dwellings distributed over building typology (detached, corner, terraced, apartment, etc.) and construction period (before 1974, 1974-1992 and after 1992).

output to achieve this, since the heating water was cold from the heat pump being off before. Note that some heat pumps have a start-up sequence for returning oil to the compressor resulting in medium to high heat output.

During the period from 12:00 to 24:00 hours, the unit is periodically switching on and off. Since the required heat output of the unit is lower than the capacity at minimum modulation it runs in a type of pulse width modulation. During a colder period from 00:00 to 12:00 hours, the unit operates at minimum capacity for an extended period, even though the supply temperature and thermostat are consistently under. Various settings on how the room temperature affects the working of the heat pump are provided by the manufacturer. These were all set to default as it was commissioned by an installer appointed by the manufacturer and not reviewed in this work.

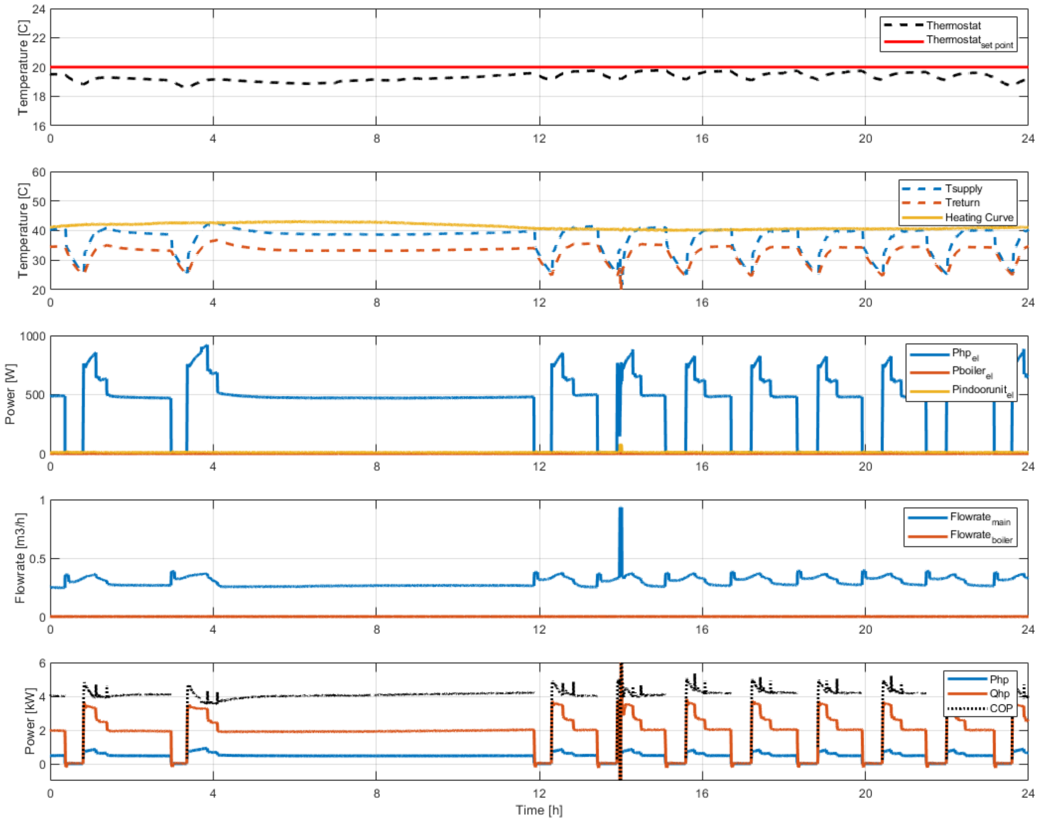

Fig. 5: The typical operation of the unit. The measurements of Case 0 on a reference weather day of 4°C.

It is important to note that there is no boiler operation during this test. The unit utilizes the boiler primarily during defrost periods, which is evident on reference weather days with temperatures of -1°C and 2°C. During defrost, the boiler reaches a maximum capacity of around 20-25 kW, causing a sudden increase in the supply temperature, followed by an overshoot in the room thermostat temperature.

4.2. The results of the parametric study

Figure 6 illustrates the daily average water temperature, COP, and thermostat temperature for each test day. Initially, radiator capacity was increased by replacing the radiators from T22 with T33 while keeping the weather compensation curve the same (from Case 0 to Case 1). As expected, increasing the radiator capacity increases the heat output of the radiators at lower supply temperatures. This heat output is actually higher than needed, as the room thermostat temperature averaged over the 3 days is above 20°C, and approximately 0.6°C higher than in Case 0. With this change, only a limited increase in COP was achieved as most of the benefit of increased radiator capacity was in improving comfort (room temperature closer to the setpoint) which was at times a bit low for case 0.

Therefore, the maximum water temperature of the weather compensation curve was adjusted from 55°C to 50°C at -10°C outdoor temperature in order to optimise the system performance (from Case1 to Case2). After lowering the weather compensation curve, the thermostat temperature remained around 20°C with a lower supply water temperature. Consequently, the COP of the system increased by approx. 0.4 (approx. 10 %) on average due to increasing radiator capacity and adjusting the weather compensation curve. In fact, the heat emitted to the house was still greater (as shown by the daily average thermostat temperature) than in the base case.

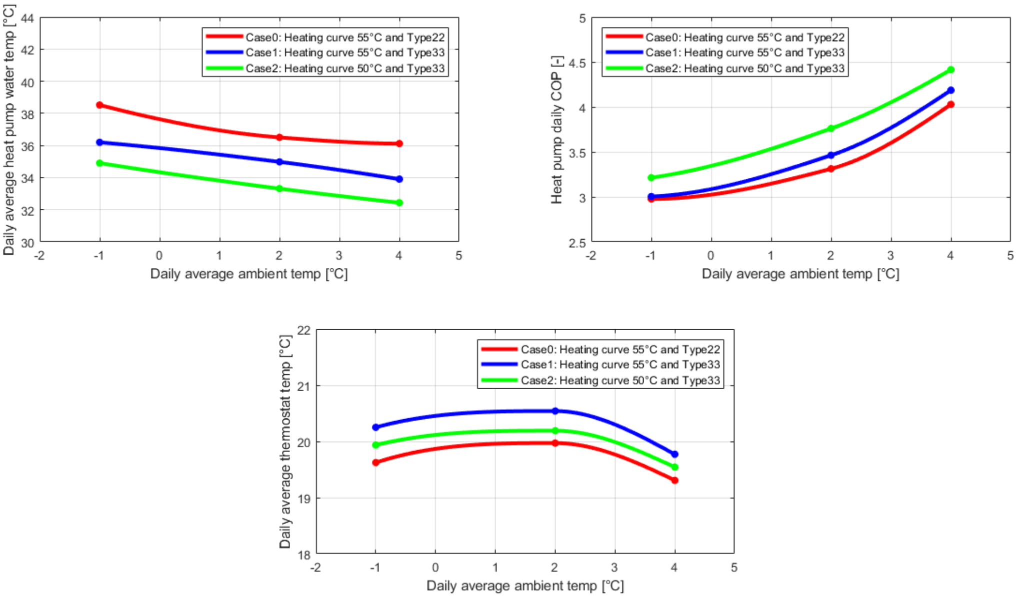

Fig. 6: Result of the parametric study; top left: daily average heat pump water temperature, top right: Heat pump daily COP, bottom: daily average thermostat temperature.

This indicates that lowering the maximum water temperature of the weather compensation curve from 55°C to 50°C (from Case1 to Case2) was not sufficient to compensate for the increase in radiator size (from Case0 to Case1). Based on these numbers it can be estimated that lowering the maximum water temperature of the weather compensation curve by another 2-3°C will increase the COP difference between Case 0 and Case 2 and will show the isolated effect of upgrading the radiator system to be higher than the found 10%.

It is worth emphasising here that these parametric measurements were carried out for -1, 2, and 4°C reference weather days only. These represent a significant part of the heating season in the Dutch climate (Nederlands Normalisatie Instituut, 2008). Therefore, it provides valuable insights into what is the impact of radiator capacity on heat pump performance. However, it is not enough to draw a conclusion about the seasonal performances. Besides, the control mechanism of this particular (hybrid) heat pump primarily relied on the weather compensation curve. The influence of the room thermostat compensation was not noticeable. Consequently, the unit conditioned the house at different room temperatures for the same reference weather day, depending on the specified weather compensation curve temperature and the defined radiator capacity. For instance, in Case 2, the thermostat temperature is higher than in Case 0. This led to more heat being transferred to the house however with better performance (COP). Therefore, directly comparing energy consumption between these cases can be misleading. With a better room thermostat compensation, the unit can maintain approximately the same thermostat temperature across all cases, allowing for a more accurate comparison of energy consumption.

Additionally, the impact of an incorrectly set weather compensation curve can be inferred indirectly from the results. In Case 0, a low weather compensation curve causes a reduction of the room thermostat temperature, which could lead to thermal comfort issues. Also, the most significant increase in the coefficient of performance (COP) occurs between Case 1 and Case 2 (approx. 7 %). This indicates that simply upgrading the heat emitter is insufficient; the weather compensation curve must be adjusted as well. This demonstrates the substantial influence of the installer on the unit's performance, especially for units without or with weak room thermostat compensation.

5. Discussion and Conclusion

The work presented in this paper demonstrates the successful creation of a HIL setup that can be used not only for obtaining more realistic system dynamics but also for facilitating comprehensive parametric studies. The repeatable nature of the setup allows for parametric studies to be performed, which is normally very challenging with standard field measurements in practice. In the HIL setup, there is complete control over the systems, meaning that the parameters can be adjusted, and the test can be run under the same conditions.

Through parametric studies, the HIL setup quantifies the impact of radiator capacity on hybrid heat pump performance. The results show that for a house with a 6 kW design heating load and a 9 kW radiator capacity at 75/65/20°C, upgrading the radiators from Type 22 to Type 33 (approximately a 50% increase in capacity) results in an increase in the performance of the hybrid heat pump by more than 10%, based on the average of three reference weather days (-1, 2, and 4°C).

An increase in the COP can indirectly influence the gas consumption in the hybrid heat pump. Typically, hybrid heat pumps switch from the heat pump to a gas-fired boiler based on the available heat pump capacity and a switchover COP, which is determined by economic or ecological considerations. Increasing the COP by lowering the water temperature thus reduces the use of gas-fired boilers and can also reduce the overall gas consumption in hybrid heat pumps.

Although this study shows that the HIL setup is quite useful in providing valuable insights into the influence of radiator capacity on heat pump performance, the test cases represent an example of a specific situation with limited weather conditions. For that reason, it is not sufficient to establish a more general conclusion between radiator capacity and the (hybrid) heat pump performance. Future work will therefore focus on extending the current study to include different construction years and insulation levels of the house, as well as varying radiator sizes (undersized, perfectly sized, and oversized) and different heat pump capacities. Additionally, the work will involve designing usable tools for assisting with techno-economic choices such as upgrading radiators.

Ultimately, more insight into this relationship can help homeowners and installers to make well-founded decisions related to selecting the (hybrid) heat pump system and changing/upgrading the heat emitter system in an existing dwelling. A financial trade-off can then be made between the costs of upgrading heat emitters and potential energy savings due to higher system efficiency.

6. Acknowledgements

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