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How to Measure and Evaluate Refrigerant Cycles – in a Representative, Reproducible Manner? An Experimental Case Study for Water-to-Water Heat Pumps

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How to measure and evaluate refrigerant cycles – in a representative, reproducible manner? An experimental case study for water-to-water heat pumps

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ABSTRACT

Today, the testing and rating of heat pumps are based on steady-state measurements, which are very well established in standards worldwide and are considered reproducible. However, the high market penetration of inverter-driven heat pumps raised concerns among researchers and policymakers about whether fixed frequency testing is representative of real operation. Especially under low load conditions, inverter-driven heat pumps adjust the compressor frequency and thus affect the unit's performance. In addition, fixed frequency testing requires support from the manufacturer, and independent testing by market surveillance authorities is impossible. Recently, the Federal Institute for Materials Research and Testing (BAM) proposed a load-based test (compensation method) to be considered the new test standard for the EU-Energy Label, which is supposed to guide installers and consumers in their choice of an efficient heating technology. It has been shown by Palkowski et al. that the developed compensation method can overcome these issues in that the compressor speed is unfixed and the native control is active during the test. The repeatability and reproducibility of the compensation method have been studied through round-robin testing by the BAM (the results will be published elsewhere). Especially under low part-load conditions, higher deviations of the calculated coefficient of performances (COPs) were observed in the RRT, which are likely linked to the various test stand configurations of the participating labs. Thus, the reproducibility of more sophisticated testing methods could be limited due to different realization of heat sinks in the test setups. This work experimentally investigates the reproducibility of a load-based testing method and suggests solutions to ensure the reproducibility even over different heat sinks (thermal inertia) in test stand setups. The compensation method serves as the basis for all measurements, and the COP measurement of a 16 kW water-to-water heat pump serves as a case study. To investigate the reproducibility of load-based measurement methods through inertia, we emulate different inertias by PT1 behavior in a Hardware-in-the-Loop environment. The experimental results show that the COP varies by up to 45 % depending on the test conditions and the emulated inertia, emphasizing the need for sound test conditions and active heat pump controllers during testing. Therefore, future test procedures must take the test stand's inertia into account to achieve comparable, representative, and reproducible results.

1. INTRODUCTION AND STATE OF THE ART

Heat pumps are a key technology to decarbonize the provision of heat in all sectors. In particular, the provision of heat in the residential sector is increasingly gaining interest to accelerate independence from gas- and oil-fired technologies. While heat pumps are an evolving technology with low market penetration compared to conventional heating technologies, for instance, boilers are an established technology. In addition, in Germany, the gas price was

significantly lower than the electricity price for decades, thus impeding the technological change from an economic point of view (Vering *et al.*, 2022).
To replace fossil fuel-based technologies with heat pumps as efficiently as possible, heat pumps must have high coefficients of performance (COP) to decrease power consumption in operation and purchase costs. Since operational costs typically exceed purchase costs due to long lifetimes (up to decades), the operating costs are extremely important for overall economic considerations. Operating costs are related to the price for electricity and the power consumption. Power consumption is dependent on the heat demand and COP. The higher the COP at a constant heat demand, the lower the power consumption. While a reduction in heat demand, for instance due to an improvement of insulation standard, is cost intensive, improvements in COP offer more cost-effective solutions (Vering *et al.*, 2021).

In general, the COP is a function of source and sink temperature (Carnot-COP), which is multiplied by an overall energy conversion efficiency $\eta_{overall}$. The latter depends on each energy conversion process in a dedicated operating point within a heat pump and considers therefore all inner thermodynamic losses that finally decrease the entire COP. Thus, when comparing the efficiencies of heat pumps, it is necessary to know the operating temperature levels (Carnot-COP) and the dedicated operating point to conduct fair assessments (Venzik, 2019). A comparable assessment is also complicated if heat pumps are no longer measured over dedicated operating points with fixed conditions but over certain periods, for instance, with unfixed frequency and active unit control. Especially, under low load conditions, inverter–driven heat pumps adjust the compressor frequency and thus affect the unit's COP due to the dependency of the compressor's frequency on $\eta_{overall}$ even at quasi-constant temperature levels. Therefore, comparative heat pump assessment is a complex and current research subject.

Today, the testing and rating of heat pumps are based on steady-state measurements, which are very well established in standards worldwide and are considered reproducible. However, the relatively high market penetration of inverter-driven heat pumps, which can adjust their heating capacity to lower loads through variable compressor speed, raised concerns among researchers and policymakers in several respects (BAM, 2019; Cadeo Group, 2020; Cheng *et al*., 2021; RISE, 2019; VHK, 2019, p. 178):

1) Steady-state testing requires fixing each test point's compressor frequency and overruling the appliance's native control.
2) Fixed frequency testing is not representative of real operation with variable compressor speed, especially under low part-load conditions.
3) To avoid on-off operation at low loads, the supply temperature is increased by an individual amount, resulting in much higher heating capacities than the prescribed heat demand and non-comparable test conditions.
4) Independent testing by market surveillance authorities is impossible since the settings of the compressor frequencies, the expansion valves, etc., must be provided by the manufacturer.

Palkowski *et al.* show in several publications (Palkowski, 2020; Palkowski *et al*., 2019a; Palkowski *et al*., 2019b) that load-based testing can overcome these issues. The compressor speed is unfixed, and the unit's native control is active during the test. Testing units in normal mode yields lower energy efficiency values, in general, narrowing the gap between lab and field performance. Therefore, a fair evaluation can promote the acceptance of the technology. For A/A heat pumps and air conditioners different projects follow a similar test approach (Ban *et al*., 2017; Cadeo Group, 2021; Canadian Standard Association, 2019; Cheng *et al*., 2021; Nakos *et al.*, 2014). Concerning A/W heat pumps and B/W heat pumps, TU Dresden, University of Stuttgart, and RWTH Aachen University (Mehrfeld *et al.*, 2020) developed, amongst others [Menegon, 2020], Hardware-in-the-Loop (HiL) environments to assess building energy systems using an entirely dynamic measurement approach. While HiL environments are used for system developments and controller assessments, load-based testing yields a straightforward comparison of heat pumps.

In 2019 the Federal Institute for Materials Research and Testing (BAM) proposed a load-based test (compensation method) to be considered the new test standard for the EU-Energy Label (BAM, 2019), which is supposed to guide installers and consumers in their choice of an efficient heating technology. The compensation method was developed by Palkowski *et al.* (Palkowski, 2020; Palkowski *et al*., 2019a; Palkowski *et al*., 2019b) in collaboration with different test institutes and is based on the same test points prescribed in EN 14825 (European Committee for Standardization, 2018). Test guidelines were published after a stakeholder consultation by BAM for air conditioners (cooling mode) (BAM, 2020a) and hydronic heat pumps (BAM, 2020b). Furthermore, repeatability and reproducibility of the compensation method have been studied recently in three round-robin tests (RRT) with an A/A air conditioner, an A/W, and a W/W heat pump, respectively (cf. Figure 1).[1]

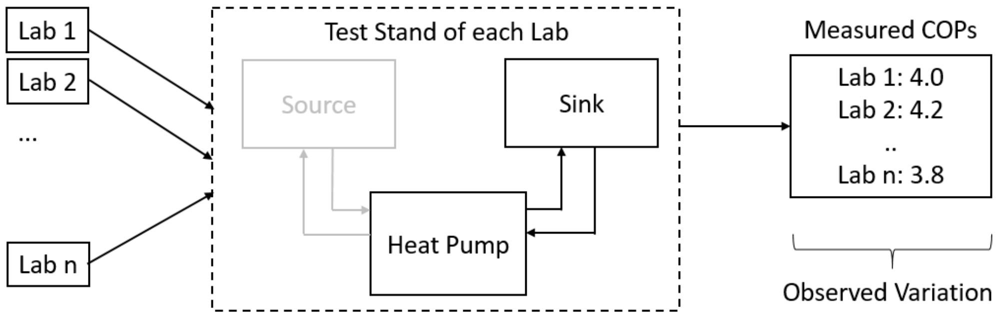

Figure 1: Schematic influence of the test stand sink side setup on the observed results in the heat pump RRTs.

Depending on the available lab infrastructure of nine laboratories, nine different test stand configurations were used in the W/W heat pump RRT. A first assessment of the RRT data revealed differences in COP, likely to be related to the different test stand inertias (sink) to a great extent. This work aims to study the influence of the test stand inertia (sink) on the measurement results.

A possible solution to emulate different test facilities and unify the test procedure is to introduce virtual thermal inertia by adding PT1-behaviour. In this work, we contribute to the unification of load-based testing methods by studying the effect of thermal inertia on the COP for pre-defined conditions from the compensation method. The emulation is integrated into a Hardware-in-the-Loop (HiL) environment, which allows the investigation of a wide range of applications. A case study measures and evaluates the COP of a 16 kW brine-to-water heat pump.

The paper is structured as follows:

- Section 2 describes the test stand and the testing method.
- Section 3 shows the results for different thermal inertias.
- Section 4 provides a discussion of all developments.
- Section 5 concludes all findings and gives recommendations for future work.

2. TEST STAND AND TESTING METHOD

To study the effect of thermal inertia on COP a test facility with very fast heat load control and emulation is required. In this context, the HiL environment from RWTH Aachen is suitable, since the setup ensures fast response of the heat sink due to a flexible admixing circuit. Figure 2 shows the general HiL setup. Each HiL application is coupled to a cloud connector, which orchestrates a HiL experiment (Müller, 2020).

Since HiL contains a real hardware and a simulation part, the simulation is used to calculate the thermal building performance, which is emulated due to a hydraulic test bench (up to 8 hydraulic lines). The hydraulic test bench is coupled to the heat pump system. For instance, the heat pump system can contain a heat pump, back-up heater and thermal energy storage. If the heat pump refers to an air-source, a climate chamber emulates weather conditions. If the heat pump refers to a water-based source, the hydraulic test stand serves as source. To apply the compensation method for heat pumps, the simulation part changes to load-based emulation and the backup heater and thermal energy storage is omitted.

The compensation method can be applied on a conventional heat pump test stand required for testing according to EN 14825, for example. In contrast to current test standards, the heat pump is tested with active control and unfixed compressor frequency. On the sink side, the unit's heating capacity is controlled by applying a constant cooling (compensation) load. The prescribed heating capacity depends on the outdoor temperature and represents the heating demand of a reference building. For ground source heat pumps (GSHP), the outdoor temperature is set with a variable

[1] The results of the three round robin tests will be published elsewhere.

potentiometer during the test. On the source side, the test stand provides a constant inlet temperature of 10 °C to the heat pump, in our tests, independent of the outdoor temperature. The test conditions are the same as in EN 14825:21018. A detailed description of the compensation method can be found in references (Palkowski, 2019b) and (BAM, 2020b).

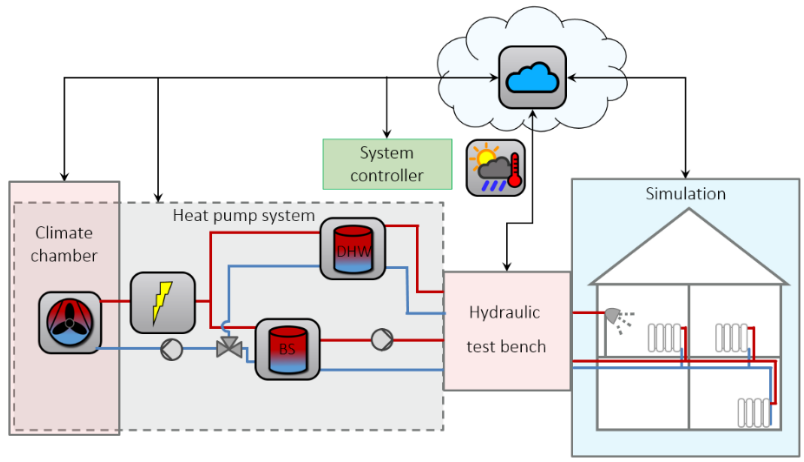

Figure 2: Hardware-in-the-Loop environment for building energy systems of RWTH Aachen.

Applying the compensation test method to study the effect of thermal inertia on COP using the HiL environment as mentioned above yields the schematic test setup in Figure 3: (1) heat pump, (2) PT1 element, (3) physical test stand inertia, and (4) heat load emulation.

(1) The heat pump is a 16 kW W/W heat pump from the RRT.
(2) The PT1 element emulates a virtual test stand inertia
(3) The physical inertia of the test rig is the inertia that cannot be neglected even by sophisticated control
(4) The thermal load emulation sets the boundary conditions of the test method.

As mentioned in Section 1, BAM observed different COPs for the same boundary conditions in other laboratories (cf. Figure 1). Therefore, we investigate the effect of thermal inertia on COP in this work. The investigation is valid due to the very low thermal inertia of the HiL environment at RWTH Aachen University due to a very efficient admixing circuit and very low water volume in the circuit due to short pipes (3). Thus, compared to other labs that were part of the RRT, the physical test stand inertia at RWTH Aachen is quasi zero, while all other labs indicated higher thermal inertia. This low thermal inertia allows the emulation of higher inertias by adding a PT1 element (1st order delay (like a low pass filter)) and thus the investigation of its influence on the COP.

In this study, the compensation method investigates three deceleration behaviors at different measurement points. The first order delay behavior (in the following called delay behavior) is assumed once as almost infinitely fast (I: 10 ms), once as medium delay (II: 1 min), and once as slow delay (III: 5 min).

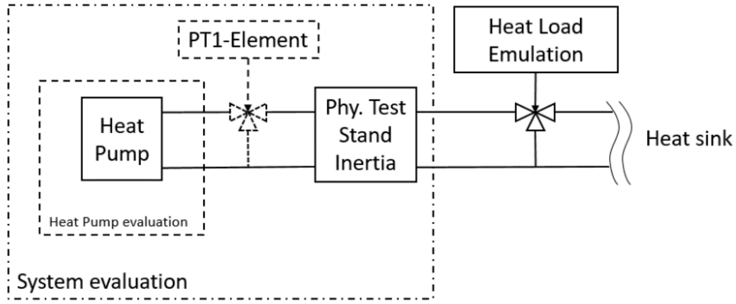

Figure 3: Schematic test setup for simulating different thermal inertia using delayed test rig response by a variable PT1 control element.

3. RESULTS

In both heat pump RRTs, higher deviations in COP were observed for the lower part loads where on-off operation of the heat pump compressor occurs. Therefore, the three lowest part-load conditions according to EN 14825, shown in **Table 1**, were chosen for this study to investigate the effect of thermal inertia (I, II, and III) on the COP.

Table 1: Test conditions according to EN 14825:2018 for a W/W heat pump with 16 kW rated capacity in an average European climate and a low temperature application.

test interval	compensation load [kW]	supply temperature [°C]	source temperature [°C]	DB outdoor temperature [°C]
B	8,39	30	10	2
C	5,44	27	10	7
D	2,33	24	10	12

Figure 4 shows the obtained results of COP for the three test conditions B, C, and D and the delay behavior I (10 ms), II (1 min), and III (5 min). For this study, no pump correction according to EN 14511 was performed, aiming to correct the influence of the circulation pumps on the COP when comparing different heat pumps. For test condition B, the three delay behaviors do not affect the COP (6.59 in each case). However, substantial differences in COP can be observed concerning the test conditions C and D. For condition C, the COP varies between 4.61 (I) and 6.66 (III), implying a relative deviation up to 30,8 % depending on the delay behavior due to the emulated test stand inertia. The same behavior can be observed in test condition D: For the delay behavior of 10 ms (I) the $COP_{D,I}$ is 3.59, while a delay behavior of 5 min yields a $COP_{D,III}$ of 6.56, which is a deviation of 45.3 %. In both cases C ($COP_{C,II}$ = 6.11) and D ($COP_{D,II}$ = 4.84), the intermediate delay (1 min) also ranks in between the other COPs. It can also be noted that the COP decreases with a higher degree of partial load (in comparison of D to C): $COP_{D,I} < COP_{C,I}$ (3.59<4.61), $COP_{D,II} < COP_{C,II}$ (4.84<6.11), and $COP_{D,III} < COP_{C,III}$ (6.56<6.66). To study the reasons for these deviations, we investigate selected time series from the individual measurements.

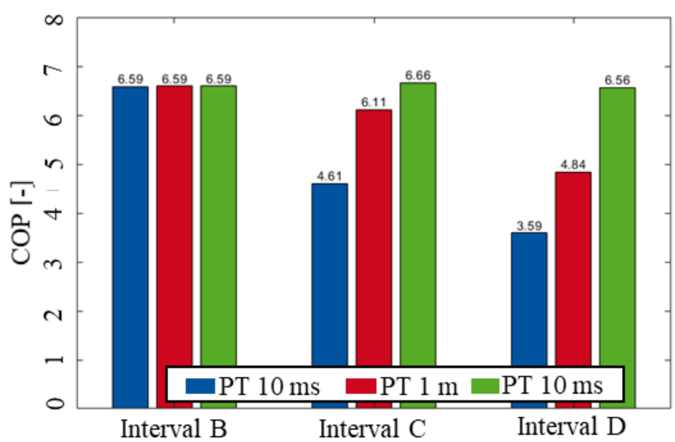

Figure 4: Test results of COP depending on test condition and on delay behavior. The shown COPs were not corrected for the electric power consumption and the waste heat of the circulation pumps according to EN 14825.

Figure 5 and Figure 6 show the time series of test conditions B and C. We provide time series for each test condition and delay behavior for relevant temperatures, thermal/electrical powers, and COP. In Figure 5, the time series are shown for test condition B at the highest part load. Under these conditions, the heat pump continuously operates at all delay behaviors (I, II, and III) and shows no on/off cycling. Thus, yielding similar average COPs. While the thermal inertia has no significant impact on the average COP, the thermal inertia influences the peak frequency, for instance, in the temperature peaks. Although the average temperatures remain quasi-constant in all setups for test condition B (I, II, and III), the frequency and amplitude differ. In case I (II) are six (two) peaks, whereas in case III only one peak remains, respectively. Nevertheless, the differences have no impact on the overall result in COP.

In Figure 6, there are the same six plots compared to Figure 5, but showing the time series under test condition C. In general, test condition C represents a lower part-load than test condition B (cf. Table 1). These differences in part-load yield a different heat pump behavior because on/off cycling occurs. The cycling reveals two findings: (1) There are big differences between the heat pump operation in test condition B and test condition C, which indicate that unfixing the compressor speed affects operation.

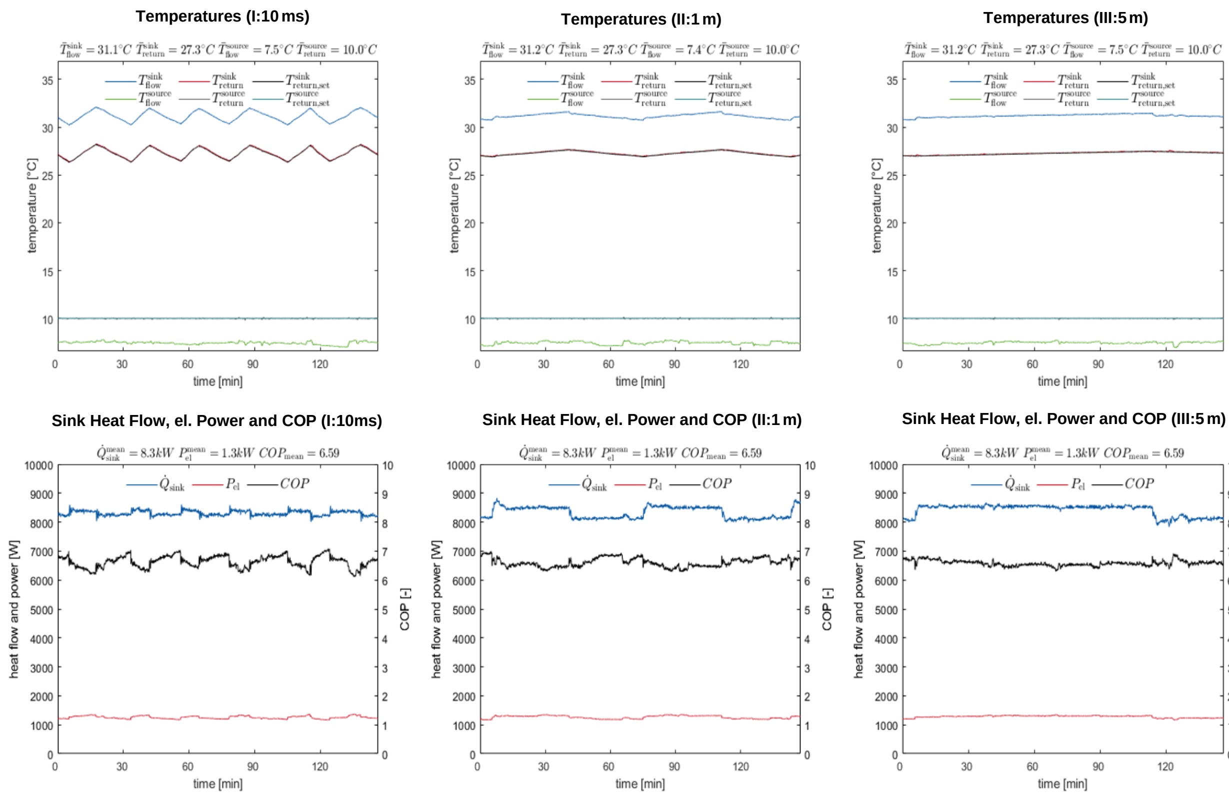

Figure 5: Measured time series and average values for test condition B of temperatures, thermal and electrical powers and COP for different delay behaviors.

In comparison, a fixed compressor frequency again would lead to another heat pump performance. Consequently, the unfixed operation should be preferred in testing and rating methods. (2) There are substantial differences between emulated test stand inertias in test condition C, which can be reduced to the three different delay behaviors. The different delay behaviors induce two reasons which lower the COP at constant average flow and return temperatures: Since a very fast test stand with low thermal inertia (case I) induces higher flow temperatures in shorter periods compared to test stands with higher thermal inertia (case II and III), the Carnot-COP in case I is lower than the Carnot-COP in case II and case III. In addition, the lower test stand inertia in case I yields more on/off cycling, which simultaneously reduces the overall energy conversion efficiency $\eta_{overall}$. Therefore, it is necessary to include the test stand inertia as a prescription for load-based testing methods to ensure comparable results. Analogous behavior can also be observed under test condition D. Test condition D is not analyzed in more detail.

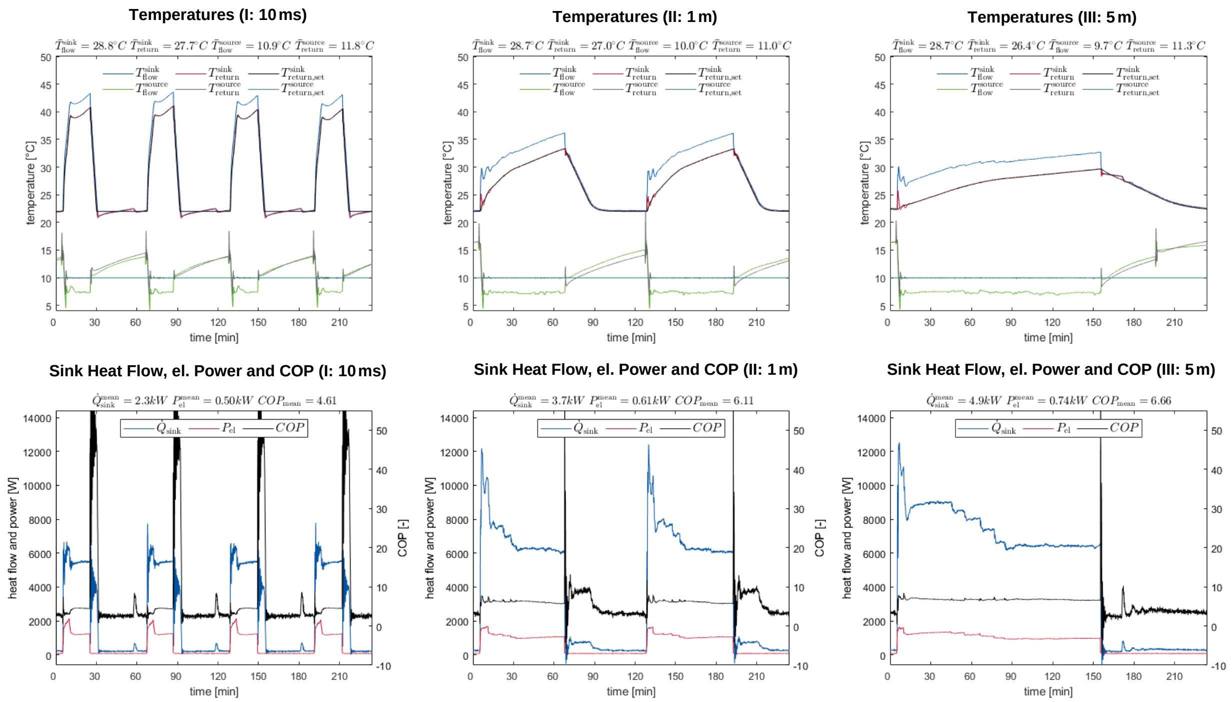

Figure 6: Measured time series and average values for test condition C of temperatures, thermal and electrical powers and COP for different delay behaviors.

4. DISCUSSION

Based on the observed total variation in COP between different laboratories in the RRT (cf. Section 1), the test stand inertia was identified as a potential reason contributing to the variations. To investigate the effect of test stand inertia on the COP in load-based testing, several measurements are conducted at different test conditions and different delay behaviors (cf. Section 3). In this context, the study's objective is to identify differences in operating dynamics. The measured differences in COP (up to 45 %) indicate a considerable influence of the test stand inertia, which lies clearly outside the measurement uncertainty. In any case, measurement uncertainty contributes to the overall distribution of test results. However, especially for this study and the significant differences in COP, it can be stated that the measurement uncertainty does not question the general observations and conclusions.

Figures 5 and 6 reveal one advantage of load-based testing that overcome current issues of steady-state tests with fixed conditions: The real operation of the unit and the underlying control strategy with the associated losses is directly measured. The measurement results indicate that the lower the part load conditions (decreasing from B to C to D), the more critical is unfixed operation. For example, while the heat pump shows no on/off cycling under condition B for different emulated delay behaviors, the COP stays constant independent from the delay. However, the unit responds differently depending on the test stand inertia for lower part-load conditions (C/D) with on/off cycling. Thus, underlining the need for load-based testing at unfixed operation and well-defined test stand inertias.

Furthermore, well-defined, technology neutral, test stand inertias contribute to the realistic emulation of heat sinks. For instance, the return temperature of an underfloor heating system is expected to respond slower due to the higher thermal mass than a radiator system in the same building, resulting in different behavior of the unit. In addition, the building type and its insulation standard will affect the rate of change of the return temperature. The considerable variation in test point C and D suggest that the test stand inertia is an important parameter to be considered for load-based testing to ensure reproducible results. Therefore, for standardization, it is necessary to define average use cases that are considered representative.

5. CONCLUSIONS

It has been outlined in Section 1 that load-based testing of heat pumps and air conditioners will become the next generation of test standards to overcome issues of steady-state testing under fixed controller conditions. While different test procedures were proposed to replace present standards, current research focuses on studying and eventually increasing the reproducibility of load-based test results. In that respect, the interaction of different controllers (unit and test stand) and dynamic phenomena under part-load conditions (e.g., on-off cycling) are often considered challenging. In addition, the variety of test stands increases the complexity to define uniform test conditions that yield comparable and reproducible measurement results.

One way to ensure reproducibility is to standardize a test stand for load-based testing in very detail. However, this could result in high investments for several laboratories and hinder the introduction of load-based test methods in performance standards and related energy efficiency policies. Therefore, this study aims to identify the main influencing parameters to develop technology-neutral test stand requirements that can be emulated with different test rigs. The emulation would allow a range of test stand configurations yielding the same test stand response.

This study shows that the test stand response (inertia) can greatly influence the heat pump's COP in part-load conditions when dynamic operation (on-off cycling) occurs. The inertia of the test stand thereby represents the building response. To allow for reproducible results, (1) ensure similar inertias between different test facilities and (2) define representative values for the test stand inertia. The first point is currently addressed by developing a calibration procedure. A calibration procedure will allow laboratories to measure their test stand response and adjust the test bench inertia before testing. This research will be published elsewhere and will include a test validation, including further labs with different test stands. Defining representative test stand inertias requires investigations that link a typical building response (interaction of building load and heat transfer system) to the delay behavior, for instance, using PT1 elements. Both aspects need to be addressed in future work and pave the way toward reproducible load-based testing procedures.

NOMENCLATURE

I, II, III	Delay behavior cases	(-)
B, C, D	Test conditions	(-)
COP	Coefficient of performance	(-)
RRT	Round-robin test	(-)

Subscript

el	electric
flow	flow
overall	overall
return	return
set	set
sink	sink
source	source

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