Steady-state Performance from Transient Measurement Data: Accelerated Performance Testing Applied to a High-Temperature Heat Pump

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Abstract

Collecting steady-state data is important in almost any experimental evaluation of thermal systems. Waiting for steady-states can take significant amounts of time and prevent researchers from more thorough data analysis or from collecting yet more experimental data at other operating conditions, system configurations or with different working fluids. This study attempts to use a relatively quickly collected transient dataset and to extract steady-state representative data from it. Apart from limiting the rate of change of operating conditions, the study found the roots of the temperature derivatives as a key to obtaining accurate steady-state representation. Test object is a 10 kW high temperature heat pump prototype with internal heat exchanger using R1336mzz(E) as the working fluid. A reduction of testing time by one order of magnitude seems feasible if a method would be developed based on this study and further research.

Keywords

Dynamic testing, transient data, steady-state, time reduction, testing method

Nomenclature

Symbols

COP	Coefficient of performance (heating mode)	-
c_p	Specific heat	kJ/(kg·K)
ΔT_{lift}	Temperature lift ($\Delta T_{lift} = T_{si,out} - T_{so,in}$)	K
$\eta_{i,o}$	Overall isentropic compressor efficiency	-
H	Enthalpy	kJ/kg
$\dot{H}$	Enthalpy stream	kW
m	Mass	Kg
P_r	Pressure ratio	-
T	Temperature	°C
t	Time	HH:MM

Subscripts

$evap$	Evaporation
si	Sink
in	Inlet
so	Source
out	Outlet
r	Refrigerant
w	Water
m	Metal

1 Introduction

Steady-state testing is frequently conducted in academia and industrial research and development. However, the testing is time-consuming due to several reasons. Specifically for the field of refrigeration and air-conditioning, those can be but are not limited to:

- The start-up and shutdown time of testing facilities like psychrometric chambers, hydraulic loops, chillers, etc., can be lengthy and must be repeated on each testing day or even multiple times a day.

- Establishing a steady-state can take significant time, especially if the system is only poorly controllable. The needed time may also depend on the skills and experience of the operator.
- The steady-state criteria may require the operation of a unit for a long time.
- Steady-states are typically collected at predefined test matrices, which requires the operator to control the system carefully until the operating conditions are met up to small deviations (it would be much faster to let the system settle at some steady-state conditions close to a relevant point of the test matrix).
- Environmental impacts can interrupt the testing. For example, if the building's mains provide the cooling water, which can decrease or change in temperature if some large water consumer in the building is activated. If the unit operation is impacted, data must then be discarded, and the steady-state must be re-established. Furthermore, equipment may be sensitive to changes in ambient temperature.
- Also, data acquisition software issues, malfunctioning components, or operators' mistakes can increase the testing time.

A few studies in the open literature have addressed this problem. Wang et al. (1987) found the performance testing of solar collectors difficult because of frequently changing cloudiness and ambient temperature. An energy balance, including the storage term, was the starting point of a filter method that achieved good agreement between results collected under changing operating conditions and those from true steady-states. The same goal was described in many studies for compressor testing and frequently addressed with complex methods as, for example, neural networks (Antonelo et al., 2018; Coral et al., 2019; Gustafson et al., 1992; Penz et al., 2012; Xu et al., 2019).

Brendel et al. (2021) also pursued a reduction of testing time and attempted to link transient data with as little post-processing as possible to steady-state data. Figure 1 (left) shows steady-state data as red points for the overall isentropic compressor efficiency for an oil-free prototype scroll compressor. The data collection required approximately two full days. The black points are transient data sampled at 1 Hz and were collected over 20 minutes. It was collected on a hot gas bypass test stand by quickly changing operating conditions to cover at least the same pressure ratios as in the steady-state data. Three post-processing steps were required to obtain the colorized data points in Figure 1 (right), which resemble the steady-state data well:

1. Discarding any data where the suction superheat was less than 1 K, because the suction gas was then in a two-phase state and the enthalpy and entropy could not be determined.
2. Applying a moving average over the last forty seconds for each data point
3. Discarding any data where the saturation temperature corresponding to the low side pressure was less than -40 °C because the compressor was designed for evaporation temperatures above -20 °C.

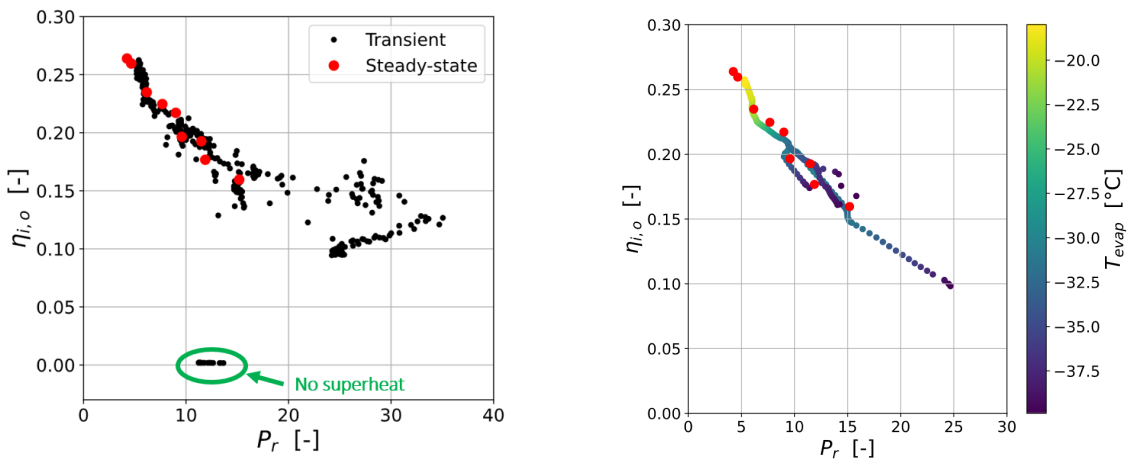

Figure 1: Transient data overlayed with steady-state data from Brendel et al. (2021) with and without post-processing.

Since the study was conducted on a hot gas bypass test stand, it remained unclear whether a similar method would be successful for a complete refrigeration or heat pump cycle. On a hot gas bypass test stand, the compressor's low and high side pressure can be changed instantaneously using valves. In contrast, the reaction time of the heat pump cycle is always slowed down by the thermal capacity of the heat exchangers. Figure 2 shows one example. Initially, the heat sink inlet and outlet temperatures are at a steady state with a temperature difference of 5 K, which is used with the sink flow rate to calculate the heating capacity. A decrease in the sink *inlet* temperature will affect the sink *outlet* temperature only after the water has flown through the complete heat exchanger, temporarily leading to a temperature difference greater than 5 K. Thus, during this time, the heating capacity is overestimated. Therefore, it is unlikely that the post-processing suggested by Brendel et al. (2021) is directly applicable to heat pumps if operating conditions change quickly. However, linking transient data to steady-state data remains and could, if successful, lead to a significant reduction of required testing time. In this case, "successful" means that the accuracy of the obtained performance results is not compromised.

Recently, a patent review was conducted for this topic with the help of "The Swiss Federal Institute of Intellectual Property". A state-of the art seach egine was fed with a range of keywords groups. Results from different groups were intersected and the results scanned manually for relevant patents. Also an artificial intelligence search was conducted based on a few related patents. The most relevant result was from Min et al. (2004), in which the authors proposed to obtain steady-state data for a gas turbine using transient data. An English version of the Korean patent could not be found, but it appears that the proposed method requires other steady-state points to obtain further steady-state points from transient data (from the abstract: "*The present invention makes it possible to predict the steady-state performance by correcting the transition state data of the engine by mathematically quantifying the difference using known properties about the steady state and the transition state of the engine.*"). Singh et al. (2009) and Si and Mou (2021) published patents leveraging an online comparison of performance with expected values, but neither tried to derive performance data from transient data.

In summary, to the best knowledge of the authors, the potential of transient data for steady-state representative performance mapping has not been thoroughly investigated in heat pump applications.

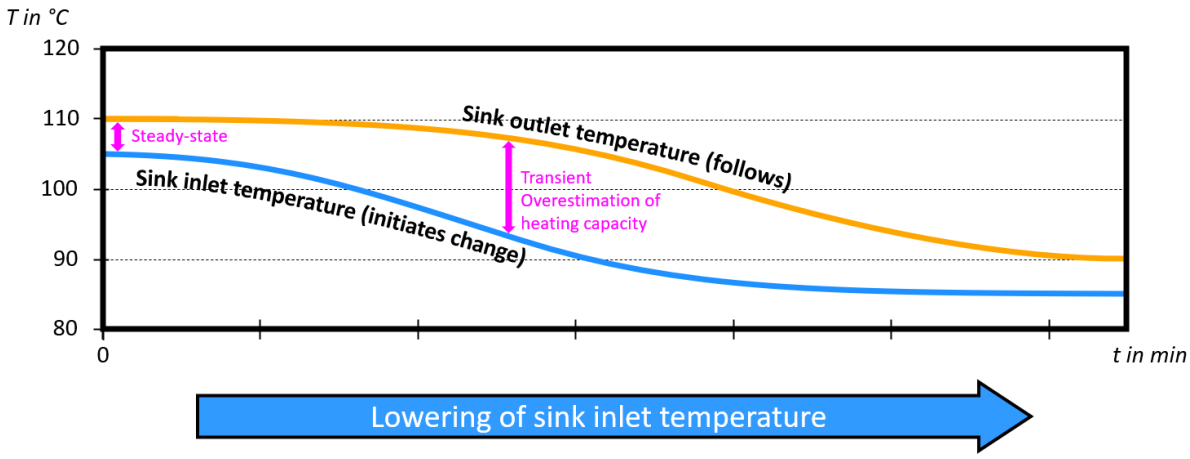

Figure 2: Thermal lag delaying decrease of heat sink outlet temperature in response to decreasing inlet temperature.

2 Methodology and steady-state results

The methodology of this study is to compare different transient datasets with a properly collected steady-state data set. The comparison shows whether a transient dataset can represent a steady-state performance data set or not.

The test object was a 10 kW heating capacity high-temperature heat pump prototype with approximately 3.5 kg R1336mzz(E) refrigerant charge. The heat pump has a reciprocating piston compressor and three flat plate heat exchangers acting as the evaporator, condenser, and internal heat exchanger between the liquid and suction line. Additionally, the heat pump has an oil separator, an accumulator in the suction line, and a receiver in the

liquid line. The heat pump is shown in Figure 3 and has been described in more detail with the steady-state measurements of R1336mzz(E) in (Arpagaus et al., 2022).

For the steady-state data, the compressor speed was set to 50 Hz, the internal liquid to suction line heat exchanger was activated, the temperature difference of the heat source across the evaporator was set to 3 K by adjusting the source flow rate, and the temperature difference of the heat sink across the condenser was set to 5 K.

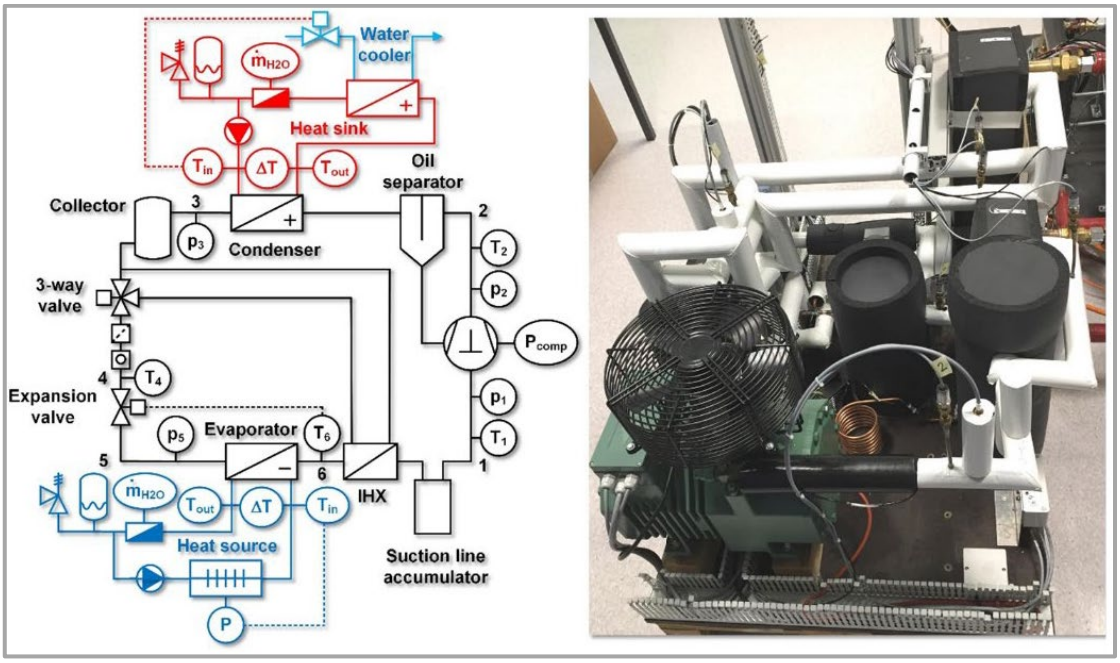

Figure 3: System schematic and picture of laboratory high-temperature heat pump.

Figure 4 (left) shows the test matrix for the steady-state testing arranged by the heat source inlet temperature ($T_{so,in}$) and the heat sink outlet temperature ($T_{si,out}$). The orange dots show a part of the test matrix with moderate temperatures for the heat pump. Blue crosses show temperatures that forced the heat pump to operate near the critical point of the refrigerant and which caused the compressor performance to deteriorate. These data points are visible in Figure 4 (right), where the COP is plotted as a function of the temperature lift ($\Delta T_{lift} = T_{si,out} - T_{so,in}$). All orange dots formed a uniform trend while the blue crosses had much lower COPs at comparable temperature lifts. The green squares show data between moderate and extreme operating conditions. The comparison of transient and steady-state data will focus on the orange area of the test matrix in this study.

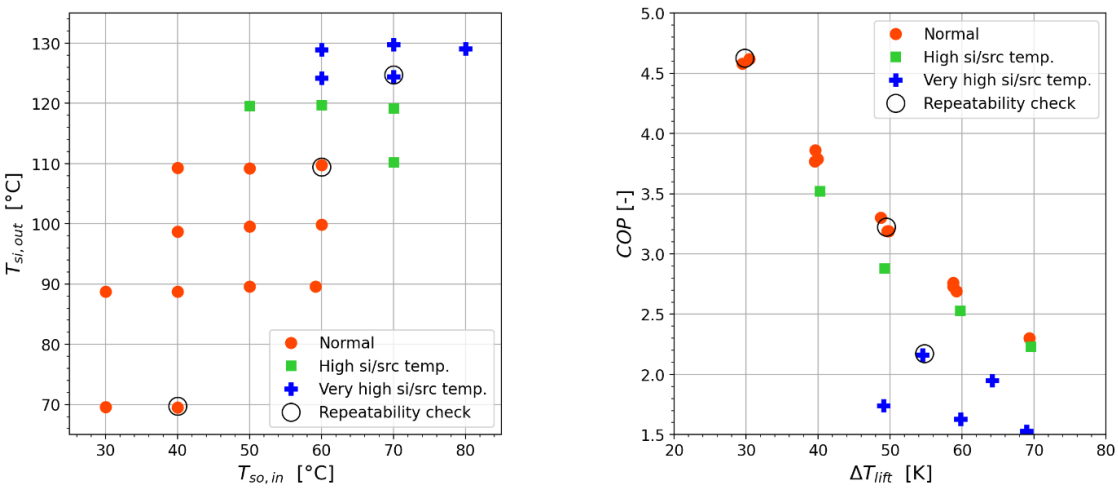

Figure 4: Steady-state test matrix and COP as a function of temperature lift (Adapted from (Arpagaus et al., 2022)).

3 Transient tests

3.1 First attempt

The initial idea was to find a transient path to cover a large part of the test matrix and change temperatures relatively slowly. Figure 5 (left) shows the path of the transient test overlaid with the original test matrix. Data was sampled once every second, and each black dot is one data point. The starting point was the reference point ($T_{so,in} = 60\ °C, T_{si,out} = 110\ °C$) and the direction of change was clockwise. Changing the temperatures along the path took approximately 2 hours. For this test, the heat sink and source mass flow rates had to be controlled manually, leading to deviations from the targeted 3 and 5 K temperature change for the heat source and sink, respectively.

Figure 5 (right) shows the same data points (one for each second) but overlaid in the $COP\ vs.\ \Delta T_{lift}$ plot with the steady-state data. Since the transient data was collected in the orange part of the test matrix, it would have to align with the orange dots to represent the steady-state data. This is the case for many data points with temperature lifts of 50 K, 60 K, and 70 K. However, some data points close to $\Delta T_{lift} = 70\ K$ underestimate the true steady-state and all data points for $30\ K < \Delta T_{lift} < 40\ K$ overestimate the COP. The first attempt was therefore judged to be promising but not sufficiently accurate in representing the steady-state data.

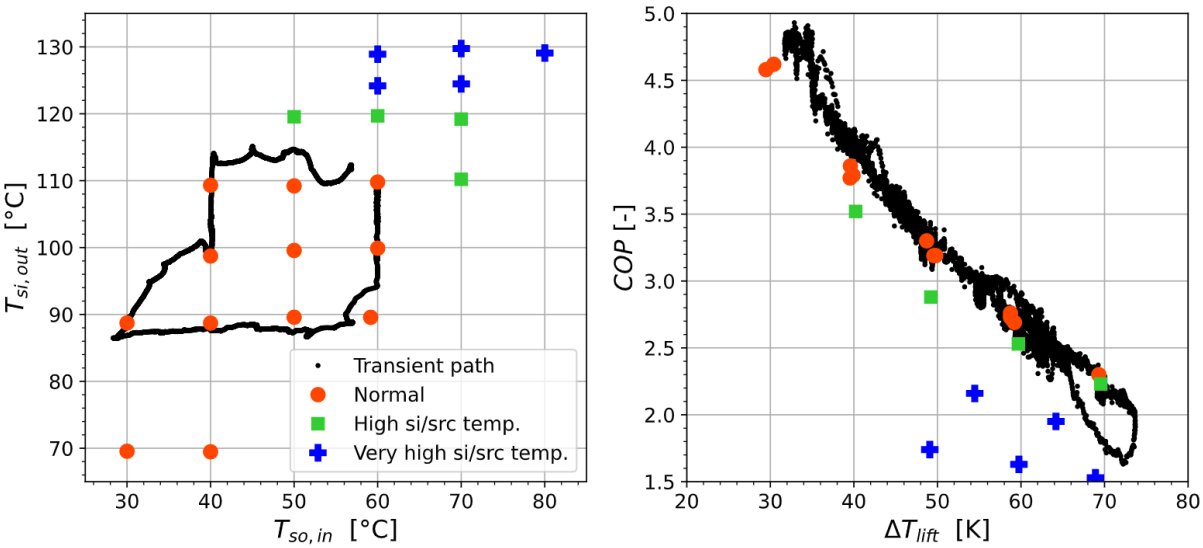

Figure 5: Steady-state data overlaid with transient data collected over 2 hours.

3.2 Second attempt

A series of three tests was conducted, where the heat source inlet temperature was maintained at $T_{so,in} = 40\ °C$ and the sink outlet temperature was varied between 70 and 110 °C (by varying the sink inlet temperature from 65 to 105 °C, resulting in temperature lifts from 30 to 70 K). The temperature was changed at different rates and directions in the three tests, as shown in Figure 6. In the first test, the sink temperature was decreased at a fast rate of 7.6 K/min. In the second test, the temperature was increased at a rate of 1.5 K/min. Finally, in the third test, the temperature was increased by only 0.5 K/min. For all these tests, a PI-controller actively changed the source and sink mass flow rate in real-time with the target of 3 and 5 K temperature difference for the heat source and sink, respectively.

Figure 7 shows $COP\ vs.\ T_{lift}$ plots for all three tests overlaid with the steady-state data. For these three tests, the effects explained in Figure 2 are comprehensible, and the impact of different rates of change is very clear:

- *Fast (7.6 K/min)*: The steady-state COP is overestimated drastically. The sink outlet temperature decreased with a delay such that the heating capacity computed from $\dot{Q}_{si} = \dot{m}c_p(T_{si,out} - T_{si,in})$ was larger than the heat rejected by the heat pump in the condenser.

- *Medium (1.4 K/min)*: The effect of the fast rate of change occurred again, but less pronounced and in the other direction. Because the sink inlet temperature increased, the temperature difference $T_{si,out} - T_{si,in}$ decreased temporarily, and therefore the COP was underestimated.
- *Slow (0.5 K/min)*: For this transient dataset, the COP at a given temperature lift is almost aligned with the steady-state data. Even though the deviation was within the measurement uncertainty, a slight systematic underestimation was still observed, and the transient data, therefore not acceptable for a steady-state performance representation.

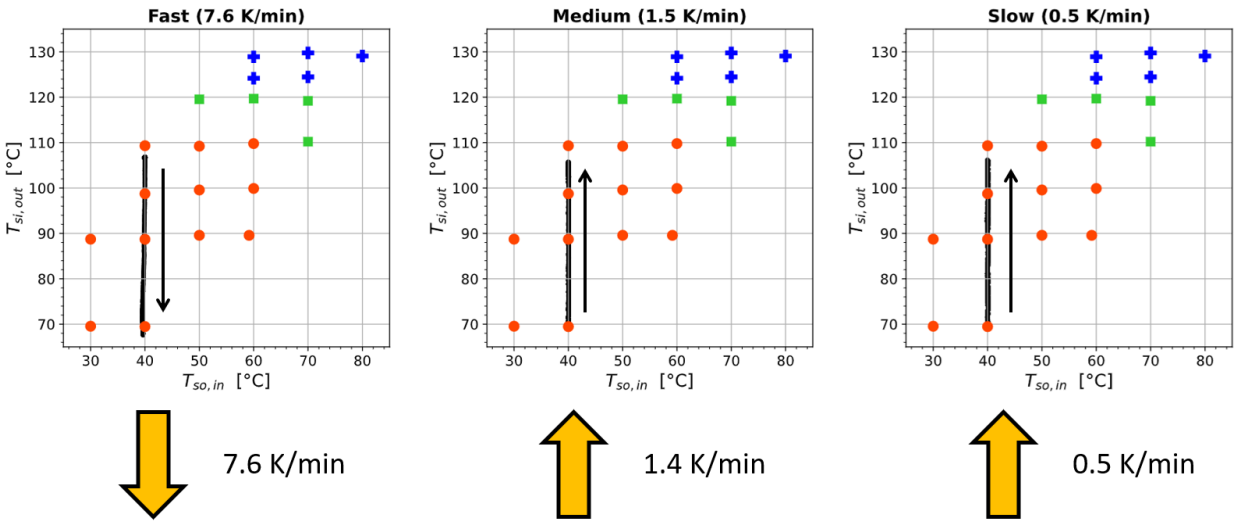

Figure 6: Transient paths for systematic study with three different rates of temperature change.

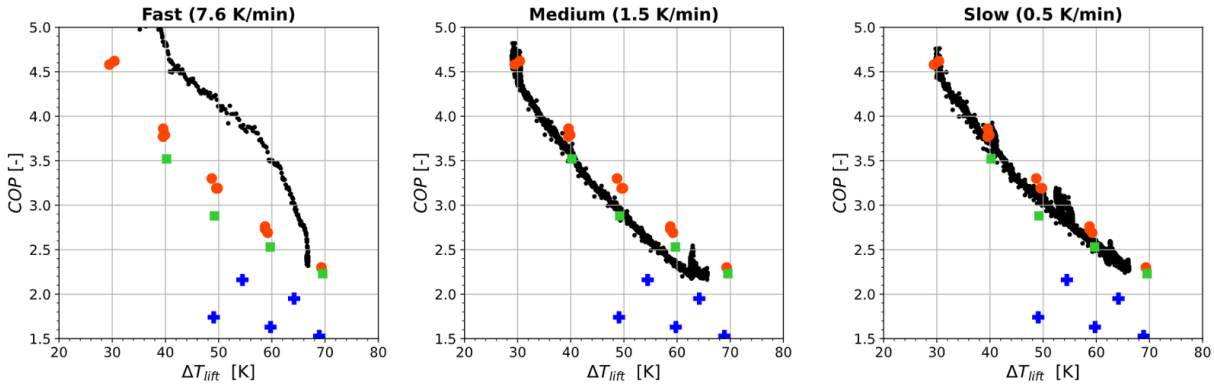

Figure 7: Steady-state data overlaid with transient data from fast, medium, and slowly-paced temperature changes.

Further insight was gained from analyzing the temperature profiles as a function of time and their first derivative, as shown in Figure 8. The derivatives were calculated using data points 60 seconds apart to smooth them and reduce the effect of noise:

$$\frac{dT(t)}{dt} = \frac{T(t) - T(t - 60s)}{60s}.$$

The following could be observed:

- *Fast*: The sink inlet temperature initiated the change after approximately 2.5 minutes in the plot in Figure 8, and its derivative quickly dropped to -15 K/min. The sink outlet and condensation temperature decreased shortly after that and had equal derivatives until approximately 3.75 minutes in the plot in Figure 8. After, the derivative of the sink outlet temperature dropped and followed the derivative of the sink inlet temperature because of the direct hydraulic connection and the short length of the heat exchanger. The derivative of the condensation temperature experienced thermal lag and dropped only to -11 K/min but recovered slower than the sink in- and outlet temperatures.

- *Medium*: The derivatives of all three temperatures were well aligned and between 1 and 2 K/min for most of the dataset.
- *Slow*: The derivatives were well aligned again. In contrast to the medium-paced dataset, the derivative also showed roots (pink diamonds in Figure 8 (right)). Those were caused by the controller of the system. Instead of changing the temperature gradually with the average rate of change of 0.5 K/min, the temperature increased too quickly and had to be lowered again to achieve the slow targeted rate of change on average. This caused small peaks and valleys in the heat sink temperature.

Data close to the roots was extracted with the condition $-0.02\ K/min < dT/dt < 0.02\ K/min$, resulting in six chunks of data, each only several seconds long (pink diamonds) which were averaged independently to result in six data points. Finally, the extracted data points were overlaid with the original steady-state points in Figure 9. The samples obtained from the transient data were well aligned with the steady-state data for all temperature lifts, although the transient dataset had never been at steady-state by any definition. The sink outlet temperature change covered by the sink pink diamonds was 36 K and required approximately 1 hour. Typically, this range in the test matrix would be investigated with 3 to 4 proper steady-state data points requiring over 4 hours.

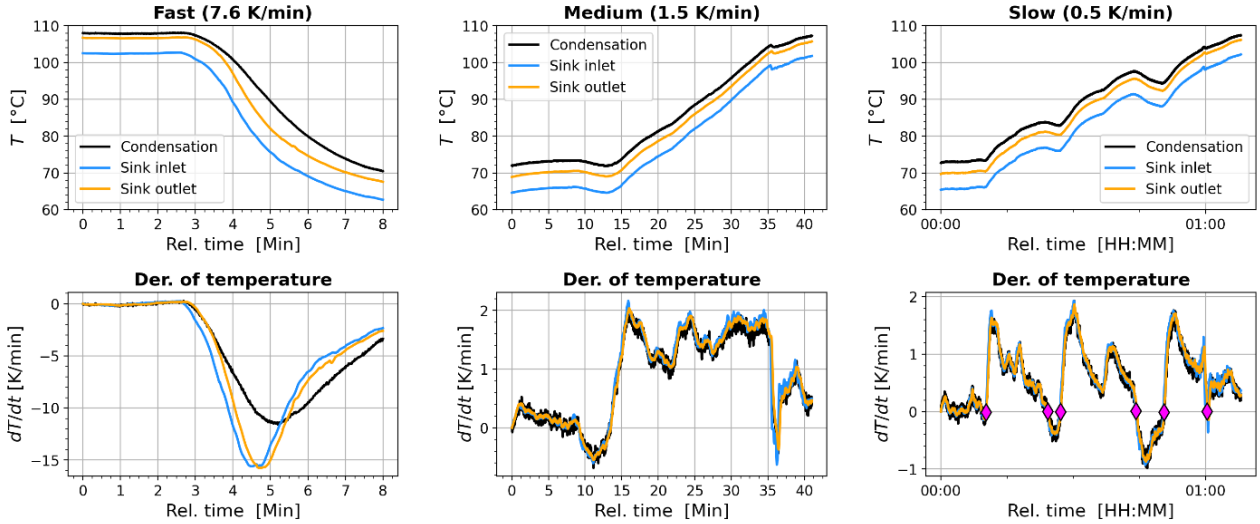

Figure 8: Sink inlet, outlet, and condensation temperature (top row) and derivatives (bottom row) for three transient tests.

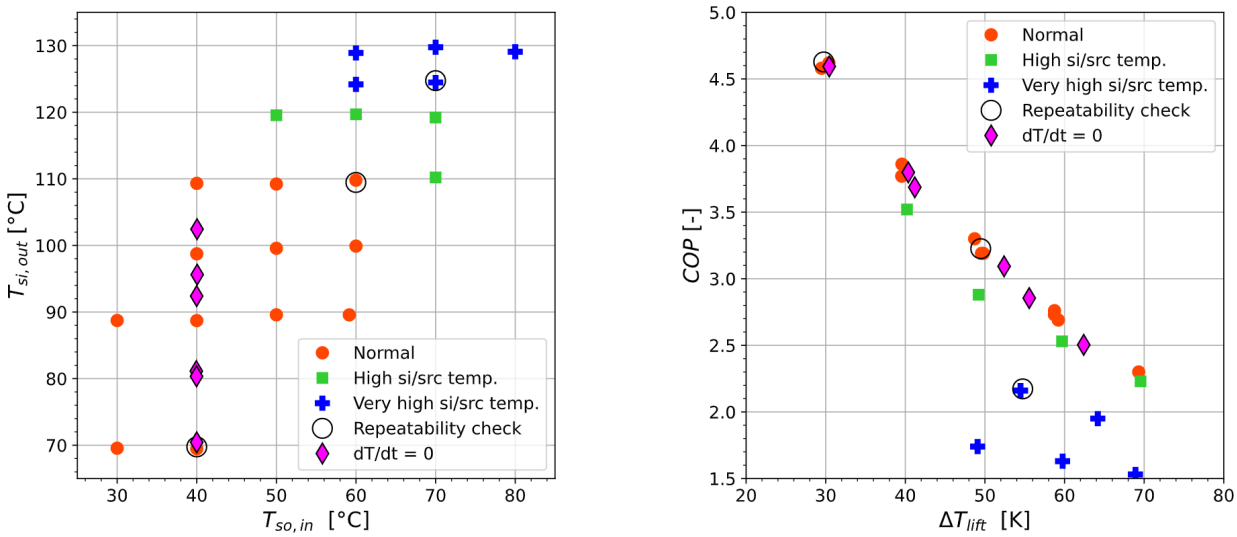

Figure 9: Steady-state data overlaid with cycle performance from root analysis.

4 Discussion

The results suggest a method to drastically reduce the testing time of performance tests for thermal systems without compromising the accuracy of the results. Three topics could lead to further improvements or finalization of the method:

- *Peaks and valleys:* Peaks and valleys could be enforced more frequently, and the operating conditions where a peak or valley should occur could be chosen deliberately. The operating conditions between peaks and valleys could be changed faster to save more testing time.
- *Up-and-down averaging:* The transient path could be followed in both directions at the same rate of change. Averaging the two transient datasets for all equivalent operating conditions may also yield steady-state representative performance data. This may even allow moving at high rates of change which by themselves lead to inaccurate results ($dT/dt \gg 0.5\ K/min$).
- *Slow changes:* There may be a rate of change so low, that the deviations of the transient dataset and actual steady-state data are smaller than the random uncertainty of the measurements). The testing time reduction would be smaller due to the slow rates of change, but the test procedure would simplify compared to leveraging peaks and valleys or up-and-down averaging. A criterion for the maximum rate of change could be found and be a function of the size and mass of relevant components.

Figure 10 shows the underlying vision of this study. The flow chart starts in the top left with some required test matrix. Conventionally, one would conduct steady-state testing to obtain the needed performance data. Instead, the test matrix could be analyzed to find an ideal transient path (direction, with/without peaks and valleys, number of paths, start and end-points of path, etc.) and a maximum rate of change, the latter requiring information about the system. The transient testing results would then undergo post-processing and yield the same needed steady-state data that would otherwise be collected in more time consuming steady-state testing.

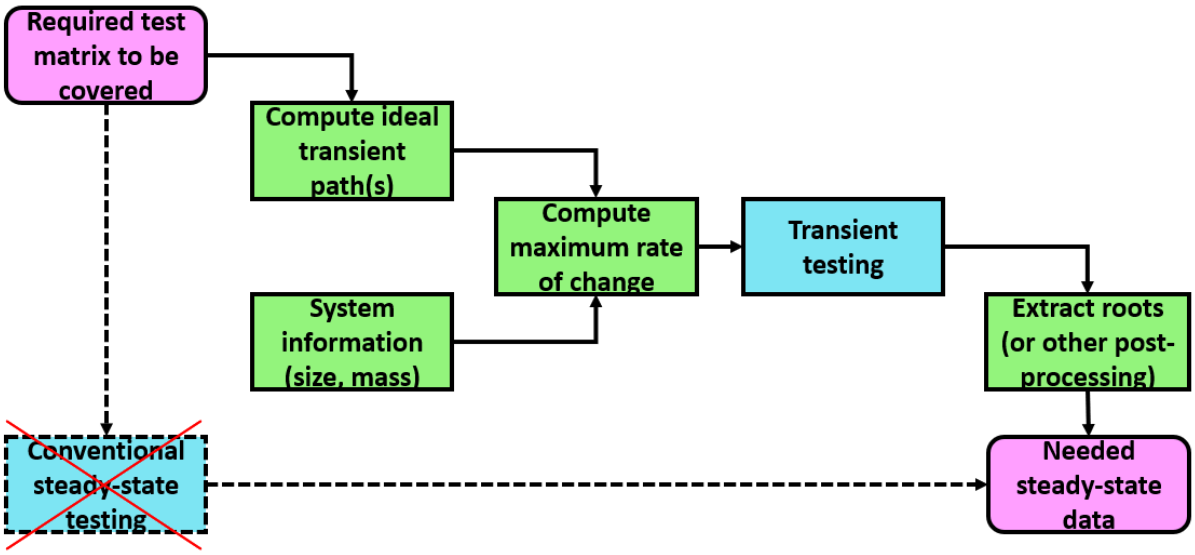

Figure 10: Flow chart of envisioned method.

Apart from the specific method, the following should be investigated:

- Can the method be used on heat pumps with different capacities?
- Can multiple operating conditions change simultaneously and still allow a steady-state representation?
- Can the method be used for other thermal systems?

The achievable reduction in testing time is difficult to predict because the method is not finalized. Furthermore, it will depend on the original test matrix, the controllability of the system, the size of the system, the steady-state criterion, and many other factors. Nevertheless, the authors estimated that a reduction by approximately one order of magnitude is possible if the method is well developed.

A physics-based criterion for the maximum rate of change still allowing steady-state representation will likely start with energy balances, including transient terms for the refrigerant, the metal, and the secondary side, exemplified here for the condenser:

$$\left(\frac{d(H)}{dt}\right)_r + \left(mc_p\frac{dT}{dt}\right)_w + \left(mc_p\frac{dT}{dt}\right)_m = \dot{H}_{r,in} - \dot{H}_{r,out} + \dot{H}_{w,in} - \dot{H}_{w,out}$$

where H is the total enthalpy of the refrigerant, $\dot{H}$ are enthalpy streams, c_p is the specific heat capacity, T is the temperature, t the time, m the mass, and the subscripts r, w, m, in and out represent refrigerant, water, metal, inlet, and outlet. The derivative of the metal temperature should always be between the derivatives of the water and refrigerant temperature. Hence, if the water and refrigerant derivatives align as in Figure 8 (center and right), the metal temperature derivative will have the same value and not need to be measured.

Finally, Figure 7 (left) clearly shows that transient testing can lead to wrong results if not applied carefully. Transient testing as discussed in this paper would also not be applicable to cyclic events as for example defrosting or the on/off cycling of compressors. As of now, the presented results do not suggest any concrete testing procedure or rate of change. Instead, the fundamental possibility of obtaining steady-state representative performance data from transient testing is demonstrated, and ideas for future research are explained.

5 Conclusions

Prior work showed that the steady-state performance of a compressor could be accurately resembled in a very short transient test with minimal post-processing. This study attempted to find a similar method for a heat pump system, which generally reacts slower to changes in operating conditions due to more thermal lag in the heat exchangers. It was found that transient data in which the heat sink inlet temperature is decreased at otherwise constant operating conditions overestimates the COP and vice versa. Furthermore, the deviation to the steady-state data decreases with slower rates of changes of the operating conditions. An exact representation of the steady-state performance was found by extracting roots from the first temperature derivative of the sink inlet and outlet temperature. Roots occurred because the temperature change was not monotonous but had small peaks and valleys. The method is still at an early stage of evaluation, and several directions for future research were identified, including a physics-based equation for the maximum rate of change, different transient paths, and other post-processing methods. The potential reduction of testing time compared to traditional steady-state heat pump operation data cannot be determined with the available data but is estimated to be up to one order of magnitude.

Acknowledgments

The work was enabled by the help of several colleagues from the Institute for Energy Systems at OST in building the test stand, most importantly the technician Gerhart Purkathofer. Valuable discussions with Professor André Bardow and Dr. Dennis Roskosch are gratefully acknowledged.

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