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Testing Standard for IHP

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ABBREVIATIONS

IHP: Industrial heat pumps
HTHP: High temperature heat pump
MVC: Mechanical vapor compression
MVR: Mechanical vapor re-compression

DEFINITIONS

Term	Explanation	Unit
Heating capacity	This refers the heat transfer rate on the sink side of the heat pump (hot side), typical identical to the thermal power at the condenser.	kW
Cooling capacity	This refers the heat transfer rate on the source side of the heat pump (cold side), typical identical to the thermal power at the evaporator.	kW
Heat pump load capacity	Part load fraction, relative to the nominal load of the heat pump. At full load, the heat pump load capacity is by definition 100 %.	%

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Introduction and purpose

A barrier for the market introduction of industrial heat pumps (IHPs) is the lack of standards on testing of such systems at high process temperatures. These standards reduce ambiguity which is critical regarding a technology where performance is dependent on the operation conditions.

The goal of this task report is to create a common benchmark method for measuring the performance of IHPs and establish a guideline which specifies methods for testing and rating of performance both for testing IHPs in the laboratory and on-site. Hence, the guideline is meant to serve as inspiration for a future HTHP testing standard. As a prerequisite for this, relevant existing standards about heat pump testing are first introduced and evaluated in relation to characterization of IHPs.

The developed guideline will also be used as a baseline and provide inputs for the test plans of the three demonstration cases in the SPIRIT project, which each are presented in the end of the report. The application of the guidelines is here discussed for each case.

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1. Existing standards

1.1. Introduction existing standards

This chapter introduces the most relevant heat pump standards used today for testing. These standards have typically been developed for space heating and air conditioning; meaning that these heat pumps are typically closed cycle compression heat pumps and operate at lower temperatures.

For industrial heat pumps, different temperature levels, refrigerants, and cycle layouts apply. Industrial heat pumps may not be closed cycle reverse Rankine compression heat pumps, but can also be open cycle reverse Rankine such as MVC or MVR. Other cycles include closed cycles such as reverse Brayton, reverse Stirling cycles, joule cycle, and thermoacoustic heat pumps, some which are outlined further below:

a) Vapor compression heat pumps (including both subcritical and transcritical cycles) are closed cycle reverse Rankine heat pumps, where a refrigerant is evaporated in contact with a low temperature source and subsequently compressed to high pressure and high temperature, where the heat is transferred to a high temperature sink, either by condensation at constant temperature (in a subcritical cycle) or by heat transfer via a temperature glide (in a transcritical cycle), see Figure 1-1 (a).

b) Gas compression heat pumps (reverse Stirling or reverse Brayton) are also closed cycle heat pumps, but without evaporation or condensation, allowing their use over a wider temperature range, but also making them more sensible to isentropic efficiency of compression and expansion. On expansion, the gas temperature lowers, allowing the gas to pick up heat at low temperature. On subsequent compression the gas temperature rises, allowing it to supply heat at high temperature.

c) MVR (mechanical vapor recompression) or MVC (mechanical vapor compression) is an open cycle heat pump used to upgrade low pressure steam (e.g. flash steam from hot water or vapor from a superheated steam drying process) to high pressure process steam, by compressing the low pressure steam flow, see Figure 1-1 (b). This technology can also be added as top cycle to a reverse Rankine heat pump that is used to provide low pressure steam.

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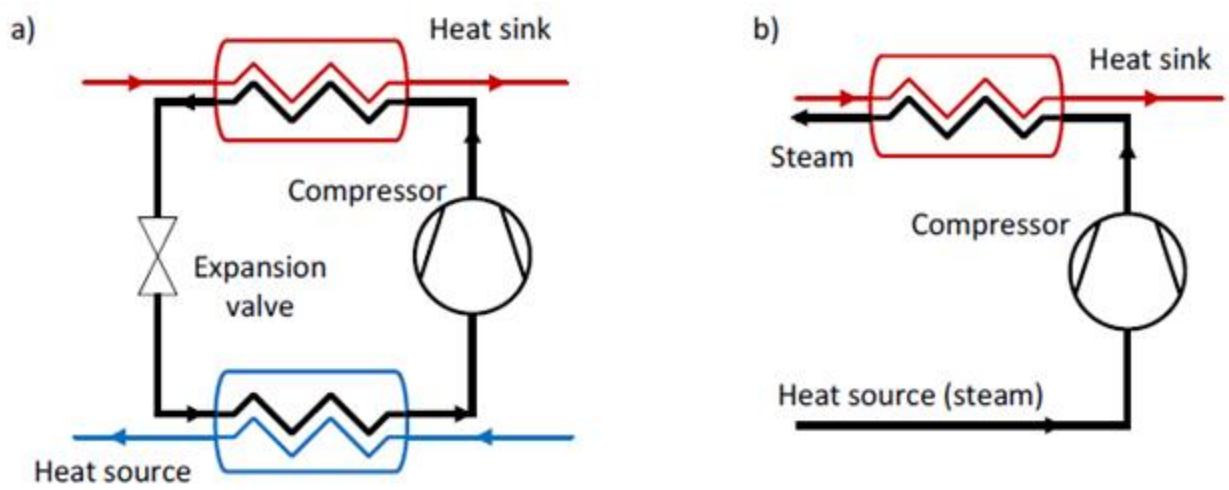

Figure 1-1: Closed cycle compression heat pump (a), open cycle MVR/MVC (b).

Furthermore, industrial heat pumps often have steam as output, requiring dedicated measurement procedures, since steam power is not fully characterized by flow and temperature, but requires the steam quality as well.

Table 1.1-1 provides an overview of the most relevant standards and their different parts, which currently used in the industry for testing domestic heat pumps:

- EN 378: Safety and environmental requirements
- EN 14511: Performance testing under steady state full-load conditions
- EN 14825: Performance testing under part-load conditions
- EN 12900: Refrigerant compressors - Rating conditions, tolerances and presentation of manufacturer's performance data
- ISO 916: Performance testing of compressor driven vapor compression refrigerating systems

Apart from these testing standards, also additional standards are relevant related more to system design of heat pumps such as for instance the pressure equipment and welding quality.

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Table 1.1-1: Existing heat pump standards – with focus on testing.

Standard	Title	Focus area
EN 378-1	Safety and environmental requirements - Part 1: Basic requirements, definitions, classification and selection criteria	Refrigerating systems and heat pumps
EN 378-2	Safety and environmental requirements - Part 2: Design, construction, testing, marking and documentation	Refrigerating systems and heat pumps
EN 378-3	Safety and environmental requirements - Part 3: Installation site and personal protection	Refrigerating systems and heat pumps
EN 378-4	Safety and environmental requirements - Part 4: Operation, maintenance, repair and recovery	Refrigerating systems and heat pumps
EN 14511-1	Part 1: Terms and definitions	Space heating, air conditioning & chillers
EN 14511-2	Part 2: Test conditions	Space heating, air conditioning & chillers
EN 14511-3	Part 3: Test methods	Space heating, air conditioning & chillers
EN 14511-4	Part 4: Requirements	Space heating, air conditioning & chillers
EN 14825: 2018	Testing and rating at part load conditions and calculation of seasonal performance	Space heating & cooling
EN 12900:2013	Refrigerant compressors - Rating conditions, tolerances and presentation of manufacturer's performance data	Rating of positive displacement refrigerant compressors, e.g. for commercial cooling applications
ISO 916:2020	Testing of refrigerating systems	Performance testing of compressor driven vapor compression refrigerating systems

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1.2. Evaluation of existing standards for characterization of industrial heat pumps

EN 378 Refrigeration systems and heat pumps - Safety and environmental requirements

This standard focuses on Safety Hazards, Safety requirements, Component Requirements and Safety testing, personal protection, operation and maintenance. The standard specifies the different hazard classes such as mechanical hazards (cuts), electric hazards (shock), thermal hazards (burns), substance related hazards (inhalation, explosion) and environmental hazards (pollution, lack of oxygen).

It describes norms that the manufacturing of the components must comply with, as well as tightness testing, materials requirements and pressure and fatigue testing. Furthermore, design should include safety issues related to unusual conditions such as high transport temperatures, persons climbing the equipment, external fire, as well as conditions that can result in excessive internal pressure. Furthermore, safety devices, access devices and controls should be designed in a way that prevents damage in case of human mistakes.

The general approach in this standard is directly applicable to industrial heat pumps as well. In industrial heat pumps, conditions will frequently be more severe, and pressures, temperatures and volumes will often be higher, but this is largely covered by the description, also indicating procedures for conditions >200 °C in the pressure testing description. Appendix E of EN 378 provides a list of refrigerants, including refrigerants typically used in high temperature applications such as butane and pentane.

EN 14511 Air conditioners, liquid chilling packages and heat pumps for space heating and cooling and process chillers, with electrically driven compressors

This standard specifies the performance testing procedure for electrically driven heat pumps and air conditioners under stable conditions, using either an air or liquid flow as heat transfer medium for either the source or the sink. However, since it is specific for air conditioning and space heating, the temperature range is a lot lower than what is relevant for HTHPs. The procedures are, however, sound and can be expanded upon for HTHP specific applications.

- Part 2 specifies the test conditions, specifying ambient temperatures and source temperature and humidity ranges, as well as sink temperature and humidity. Because of the focus on space heating and tap water heating, the heating mode sink

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temperatures are in the range of 20 °C (low temperature space heating) to 65 °C (tap water heating). For the cooling mode, sink temperatures are specified in the range of 7-18 °C. Obviously, for industrial heat pumps, higher temperature levels have to be specified, that are related to the process conditions under which these heat pumps have to run, e.g. for providing process steam in the temperature range 130-180 °C.

- Part 3 specifies the test methods. In particular, corrections are specified for thermal power and electric power, related to the fan performance and lab conditions. Also, other effects affecting the performance measurements are mentioned, such as pressure drop by orifices. Conditions should be measured under steady-state. A listing of KPI's is also specified, such as electrical power, thermal power and COP, in heating mode, and cooling mode, and for the electricity also in standby mode and off-mode.

- Part 4 specifies requirements to be specified by the manufacturer, such as the range of operation, type of oil, filling of refrigerant etc., as well as other instructions for the installer. Also, start-up performance should be tested, related to e.g. restart after power blackout, and noise level and startup current should meet the corresponding norms.

Whereas part of the standards clearly applies for HTHP, other aspects have to be modified. The most obvious one is the temperature ranges specified for the testing, that clearly don't apply to industrial conditions. Furthermore, aspects like start-up current or noise production are completely different in an industrial environment as compared to domestic application.

EN 14825 Air conditioners, liquid chilling packages and heat pumps, with electrically driven compressors, for space heating and cooling – Testing and rating at part load conditions and calculation of seasonal performance

This standard is somewhat similar to the previous EN 14511, but specifies the performance testing procedure for electrically driven heat pumps and air conditioners under part load, which is defined as related to the actual temperature difference compared to the design temperature difference; if the actual ambient temperature is lower than the design temperature, a chiller will have a better performance (lower lift), or a heat pump a lower performance (higher lift). The performance for chillers is measured under part load ratios of 100 %, 74 %, 47 % and 21 %, corresponding to ambient temperatures of 35 °C, 30 °C, 25 °C and 20 °C, as compared to the reference ambient temperature of 35 °C. Furthermore, calculation methods for the seasonal EER and

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COP are presented. For industrial heat pumps, the effect of changing source temperatures is generally not relevant, since the source temperature is normally determined by the process waste heat temperature that is fixed independently of ambient conditions.

EN 12900:2013 Refrigerant compressors - Rating conditions, tolerances and presentation of manufacturer's performance data

This standard aims at providing a standard to support comparison of different refrigerant positive displacement (piston) compressors. The standard refers to the proper determination of electric power, refrigeration capacity and COP, both for full load and part load. The standard provides dedicated reference temperatures for different refrigerants, particularly CO_2, NH_3, 'Halocarbons, hydrocarbons and blends' and 'other refrigerants', as well as allowed tolerances in actual performance (power uptake, refrigeration capacity, COP) compared to published data. This standard could thus be relevant for testing of compressors intended for HTHPs.

ISO 916:2020 Testing of refrigerating systems

This standard applies to the performance testing of vapor compression refrigerating systems, including conventional types such as turbo, screw, and piston compressors (but not absorption or steam jet). The standard refers to how the thermal refrigeration capacity and electric power absorbed should be determined and specified in warranties, taking into account variations in operating conditions and acceptable tolerances in measured performance. Tests should be based on two consecutive measurements done in steady state for a sufficiently long time, with clean external heat exchanger surfaces and under operating conditions as agreed to. Minimum accuracies for temperature measurements, power measurements and flow measurements are specified, as well as for the determined heat balances. The standard is not specific to a certain temperature range, and so parts are also relevant for HTHPs.

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2. Guideline for testing HTHP's in the laboratory

The characterization of the heat pump system can take place in a laboratory when characteristics such as the size, capacity and configuration allow for testing in a laboratory. However, industrial heat pumps are not always plug-n-play systems, and some heat pumps have to be integrated directly into the process and tested on site.

But for heat pumps that can meaningfully be tested in the laboratory, all the external conditions affecting the operation of the heat pump must be controlled. The type of tests needed to characterize the heat pump's performance under laboratory conditions are:

- Full load test
- Partial load test
- Ramping tests
- Stand-by test
- Off-mode test

Which are described in the following sections.

The uncertainty of the measuring devices to consider has been defined in standard EN-14511:3-2022. It is recommended that the uncertainties of the measured values shall not exceed the values listed in table 2-1.

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Table 2 – 1: Uncertainties of measured values based on 14511.

Measured quantity	Uncertainty of measurement	Unit
Liquid		
Temperature difference	± 0.15	K
Temperature inlet/outlet	± 0.15	°C
Volume (mass) flow	± 1 %	m^3/s (kg/s)
Static pressure difference	± 1 kPa (Δp≤20 kPa) or ±5 % (Δp>20 kPa)	kPa
Air		
Dry bulb temperature	± 0.2	K
Wet bulb temperature	± 0.4	K
Air volume flow	± 5 %	m^3/s
Static pressure difference	± 5 Pa (Δp≤100 Pa) or ± 5 % (Δp>100 Pa)	Pa
Refrigerant		
Pressure at compressor outlet	± 1 %	kPa
Temperature	±0.5	°C
Concentration (in volume)		
Heat transfer medium	±2	%
Electrical quantities		
Electric power	±1 %	W
Voltage	±0.5 %	V
Current	±0.5 %	A
Compressor rotational speed (for open type compressors)	±0.5 %	min^{-1}

2.1. Full load test

For the **full load tests** the performance of the heat pump under steady state conditions is measured and the average of each value over time is used for its performance characterization. These results will provide information on the performance of the heat pump at different operating conditions.

The data considered belongs to the "data collection" period. For better results the data collection period must follow a "preconditioning period" in which the heat pump operates for a minimum required period of time. This period must be enough to allow all components to reach thermal equilibrium before the data collection period starts.

The heat pump operating conditions are defined by the manufacturer. The operating temperatures of the heat pump are basically the temperatures that the system can

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operate in for the heat source and the sink side. For the characterization it is advised to select a minimum of five operating conditions at the heat source and sink sides, within the range provided by the manufacturer. The specific temperature conditions could be equally spaced and spread within the operating range of the heat pump. In this way, the performance of the heat pump can be evaluated for different type of applications and conditions applicable to different process requirements and temperature lifts.

For example, the testing plan for a heat pump with operating range of conditions of 60 to 80 °C in the heat source side, and 100 °C to 140 °C on the sink side the full load test conditions in Table 2.1-1 could be considered. In some operating points the pressure ratio could exceed the maximum of the heat pump, for example in the case of 60 °C source/140 °C sink. For those case scenarios the testing point are not considered.

Table 2.1-1: Testing matrix example for a HTHP.

Heat source inlet temperatures [°C]	Heat sink outlet temperatures [°C]				
	100	110	120	130	140
60	X	X	X	X	X
65	X	X	X	X	X
70	X	X	X	X	X
75	X	X	X	X	X
80	X	X	X	X	X

The flow rates in the source and the sink side could be set as stable under a "nominal operating condition". Considering the example testing matrix of Table 2.1-1, the flow rate could be fixed for the case of T_{source} 70 °C and T_{sink} 120 °C. For the rest of tests the flow rate will remain equal and the ΔT in the source and sink sides of the secondary flows will change accordingly.

2.2. Partial load test

For heat pumps that are capable of operating under partial loads it is necessary to characterize their performance under partial load operation. There is more than one method to control the heating capacity of a HTHP, which could be via the electric input,

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the internal valves of the compressor, by-passing vapor, or other methods. Every type of capacity control has a range of operations considering the lowest as the "minimum load" and the highest capacity as the "maximum load".

For **partial load tests** it is suggested that the heat pump operates at a minimum of three (3) different capacity loads. The range of loads differ from manufacturers therefore the values can be adapted according to each HTHP system. An "intermediate capacity load" can be considered to provide an intermediate operating performance. For each load, three temperature lifts can be considered to provide further performance curves. In addition it needs to be considered that the full load tests might already have been tested in the "full load testing" campaign, therefore it might not be necessary to repeat these tests. An example of the suggested tests and the way they could be presented is illustrated in Table 2.2-1.

Table 2.2-1 - Example of partial load testing conditions.

Capacity load	HP temperature lift [K]	COP [-]
Maximum load	50	3.2
	40	4.9
	30	6.0
Intermediate load	50	3.0
	40	4.5
	30	5.5
Minimum load	50	2.5
	40	3.8
	30	4.5

2.3. Ramping tests

The gradual increase or decrease of the compressor speed (RPM) is defined as a "ramp". To estimate the response of the heat pump to the thermal load variations, **ramping tests** are also suggested. These tests show the performance of the HTHP during sudden high load changes that could happen during start-up and shut-down

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phases of the system, and might also provide insights whether the heat pump can provide possible ancillary services for the electricity grid.

For the ramping tests the HTHP basically starts from stand-by mode, and it is set to deliver the load at the required temperature in the sink side. The time to reach the required conditions could differ depending on the heat pump type, the set points and the internal control parameters. The operation of the HTHP and the time is monitored until it reaches a demanded load (**ramp-up**).

The same strategy when applied inversely where the heat demand drops is called **ramp-down** test. The time needed to get from stand-by mode to a required T_{HPlift} is measured providing an overview of the reaction time of the heat pump under maximum operation requirements (see Figure 2-1). In cases where the heat pump follows a ramp down pattern during shut-down, it is important to measure the time needed, since the energy consumed during this period of time is considered as losses. This amount of energy lost can be substantial when the heat pump operates in large number of cycles during the year.

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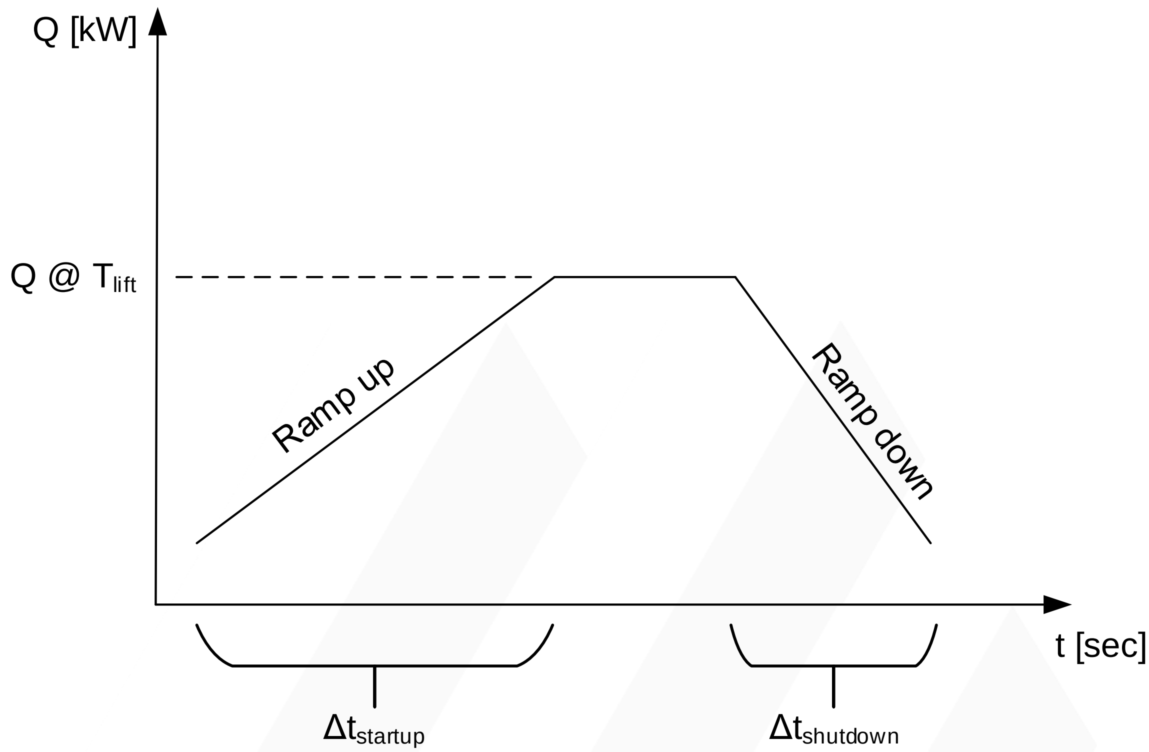

Figure 2-1 : Schematic showing the ramping tests delivered at minimum and maximum HP temperature lifts and the time reaction of the HP.

2.4. Stand-by test and off-mode test

The **stand-by test** is intended to evaluate the energy/power consumption of the heat pump during its stand-by phase. Heating elements, circulation pumps for internal loops or electronic devices could be responsible for auxiliary energy consumption during the stand-by phase of the heat pump. This type of energy consumption could have an important impact on performance if the consumption is substantial.

The **off-mode test** includes the measurement of the power consumption of the heat pump during off-mode phase. This could involve any type of systems that are meant to protect or monitor the heat pump system during long term off mode periods. They could be heating elements, any consumption of the electrical cabinet, etc.

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2.5. Test apparatus and procedures

Measurements

The measurements that must be considered for high temperature heat pump testing are shown in Table 2.5-1.

Table 2.5-1: Measurements for HTHP testing.

Ambient site conditions	- Air temperature (°C) (inside the testing room) - Humidity - Atmospheric pressure (kPa) - Ventilation rate
Electrical quantities	- Voltage (V) - Total Current (A) - Total Power input (kW)

Thermodynamic values	- Working fluid loop(s):
	  o Temperature (°C)
	  o Pressure (kPa)
	  o Non-intrusive mass flow rate (kg/s)
	- Secondary loops:
	  o Temperature (°C)
	  o Pressure (kPa)
	  o Mass flow rate (kg/s)

Noise	- From enclosure of HP
Vibration	The vibration coming from the enclosure of the heat pump or from the metallic frame of the setup could be measured. The reason is to ensure that the location is safe for the heat pump installation. The values to be measured could be: - From the enclosure Amplitude (g's) - Frequency (Hz)

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Calculated values

The values to be calculated are listed below:

- *Heating capacity*. This refers the heat transfer rate on the sink side of the heat pump (hot side), typical identical to the thermal power at the condenser.
- *Cooling capacity*. This refers the heat transfer rate on the source side of the heat pump (cold side), typical identical to the thermal power at the evaporator.
- *Coefficient of performance* (COP)
- *Lorenz efficiency*
- *Heat pump temperature lift* ($T_{HP,lift}$). Defined as difference in heat sink outlet temperature and heat source inlet temperature.
- *Steam superheating degree*

Other additional optional values

- Isentropic efficiencies
- Volumetric efficiency
- Steam quality % (in case of steam HTHP)
- Oil data (moisture, acidity, viscosity – minimum operating period must be defined)
- Refrigerant data (water content, oil content, impurities)

Measurement points and procedure

The **points to measure** in the HTHP setup are illustrated Figure 2-2. For the secondary loops (water/air/other) the measurements of temperature, pressure and mass flow rate at the heat source (evaporator) and heat sink (condenser) must be considered. If additional heat exchangers require secondary flows (subcooler, etc.) their temperature, pressure and mass flow rate must be measured as well.

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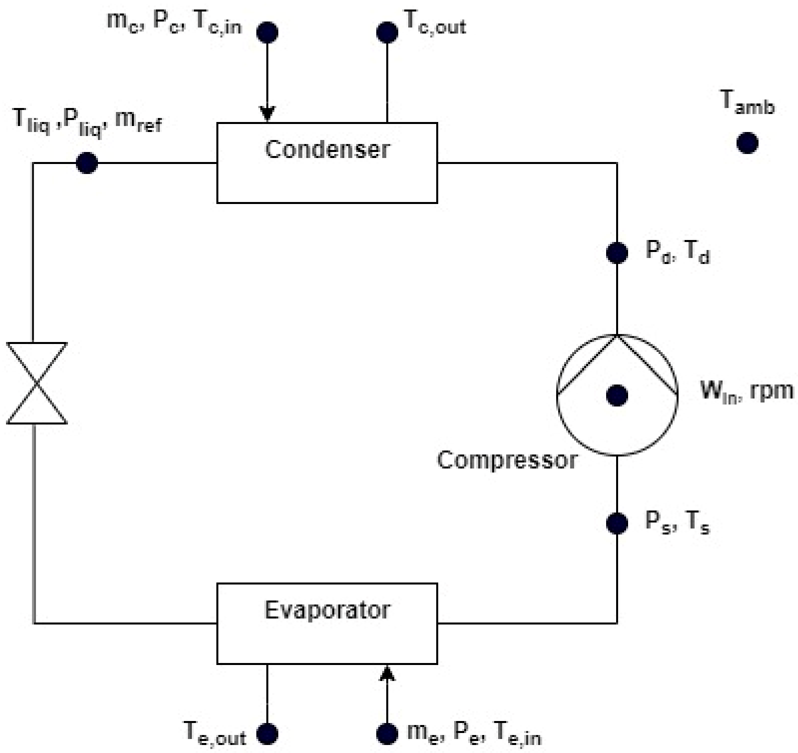

Figure 2-2: Schematic of a basic heat pump layout with the required sensors shown.

On the refrigerant side, suction and discharge temperatures and pressures are measured near the compressor ports. The compressor electricity consumption and speed must be also measured. The temperature of the condensed liquid at the condenser/subcooler outlet as well as the mass flow rate is important to be measured. Finally, the ambient temperature conditions are also monitored to define the losses of the setup.

The measurements needs to be noted when the system is in steady-state. According to EN 14511-3: 2018, there are several steps to follow to identify whether the heat pump operates in steady state conditions, which can be used as a reference for this guideline.

The preconditioning period ends when the test tolerances specified in Table 4 of EN 14511-3: 2018 are attained for at least 10 minutes and is followed by an equilibrium period of one hour in which the tolerances should be met.

Hence, the data collection period lasts a minimum period of 70 minutes, in which data must be sampled at equal intervals of 30 seconds or less. For each interval of 5

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minutes during the data collection period, an average temperature difference shall be calculated $\Delta T_i(t)$. The average temperature difference for the first 5 minutes of the data collection period $\Delta T_i(t = 0)$ is used for calculating the following percent change:

$$\%\Delta T = \left[\frac{\Delta T_i(\tau = 0) - \Delta T_i(\tau)}{\Delta T_i(\tau = 0)}\right]$$

If during the data collection period the $\%\Delta T$ of the measured values do not exceed 2.5 % and the test tolerances specified in in Table 4 of EN 14511-3: 2018 are satisfied, the operation is considered steady-state.

Test results

Looking at the key test results, they could include:

- COP
- Heating capacity [kW]
- Cooling capacity [kW]
- Required electricity consumption
- Response time

The results can be used for making a performance label, which potential could look as shown in Figure 2-3, showing the performance in the various operating conditions and the noise and vibration measured values.

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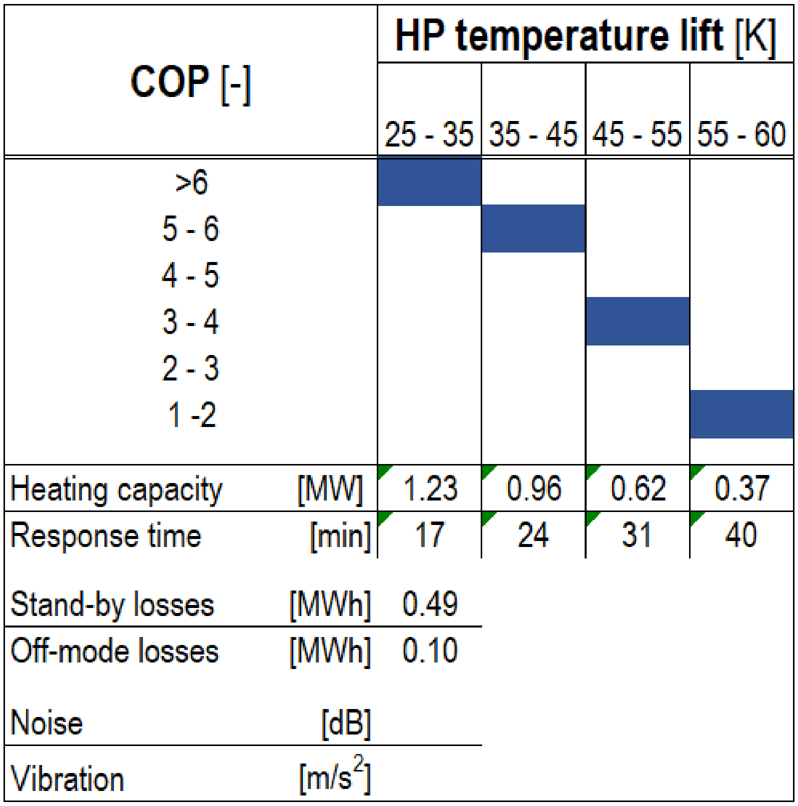

Figure 2-3: Example of heat pump performance test label.

In this example, the heating capacity is shown in certain intervals for the average temperature lifts, and the response time is calculated from stand-by mode and ends when the heating capacity are in steady state, as defined in the above section **Measurement points and procedure**. In addition to this the losses are shown, which can be multiplied by the time to find the total energy loss in stand-by and off-mode in a given time interval.

3. Guideline for testing on-site

During site testing, and SAT, the heat pump experiences real operating conditions from start-up to full load, hence there are naturally more fluctuating boundary conditions and changes in ambient conditions around the heat pump compared to testing in the laboratory. At the same time, there are most likely a series of constraints to the possibility of changing these boundary conditions, leading to a limited operating area for the heat pump.

The purpose of this chapter is to describe a site testing guideline that can be used to ensure the buyer of the heat pump has a purchased a well-functioning heat pump

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that lives up to the specifications agreed upon together with the heat pump contractor/supplier. Testing on-site allows one to test the heat pump with the capacity that the heat pump was designed for, without the limitations that a laboratory may have. Moreover, the site has the correct electrical installation prepared for the heat pump.

3.1. Specification of site testing

Under the specifications agreed upon, the test procedure is recommended to focus mainly on verifying the:

- COP
- Temperature values and glides for the sink and source side
- Thermal output power
- Electrical power

The following is a general checklist of measurements to be performed during the SAT:

- Thermodynamic values of the process
  - Sink and source flows (including all sub-flows such as injection water for desuperheating steam, any flows that the sink or source might be split into, flows for open systems where part of the sink flow is lost to the process, etc.)
  - Auxiliary flows (water for oil cooling, steam used for a startup heat exchanger, etc.)
  - Inlet and outlet temperature on sink and source
  - Inlet and outlet pressure on sink and source
  - For steam generation and vapor condensation determine the outlet quality
  - For humid air determine inlet and outlet humidity
  - For bulk products in drying processes it can in some cases be necessary to determine the inlet and outlet temperatures, and also the inlet and outlet water content
- Ambient/site conditions
  - Temperature
  - Humidity
- Electrical data as consumed by the entire HP system
  - Voltage
  - Current
  - Power

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- Data collection period
    - Length of measurement period that values are averaged over
    - Sampling rate
    - Maximum deviations of measurement values
    - Standard deviation of measurement values
    - Mean values of measurement values

Besides the performance testing, it is also recommended to include a functionality test of the heat pump system, which checks that the requirements for **noise**, **vibration levels**, and potential **Atex equipment** in the various operating conditions are fulfilled. Furthermore, leakage and pressure testing according to EN-378 also needs to be made.

The suggested method for performance testing matches closely with the procedure described in ISO 916:2020, related to performance warranties for refrigerating systems, which can therefore be used for inspiration for site testing. In the ISO916 standard, the following specification is given: "Only the characteristics essential to the economic efficiency and the operation of refrigerating systems and verifiable by usual measurement methods shall be the subject of performance warranty. This requires allowances for the variations of operating conditions which are hardly avoidable in practice (ISO 916:2020)." The standard therefore focuses on cooling capacity, electrical power uptake by the compressor, electric power uptake by the entire system and the calculation of the COP. The standard refers to performance in steady state for operating conditions as agreed previously, taking into account allowed tolerances in operating conditions and sensor uncertainty.

The measurement deviations and uncertainties that can be accepted for the site test, must be agreed upon before a test result can be noted in a given test point. The expected deviation can depend on both the heat pump technology and the given application. Various tables for such expected tolerated deviations can for instance be found in ISO 916:2020 and EN-13711. It is in this guideline recommended to specify the acceptable deviation for selected key measurements. The choice of the key measurements will depend on the given application and the heat pump type but could for example be as listed in Table 3.1-1. If the variability of the measurements is not known beforehand, the site test should span a period long enough to establish this variability. Once this is done, a time period of minimum 30 minutes can be selected where the variability is within the acceptable deviations. This period is then defined as steady-state mode.

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The test measurements must then be taken as the mean values across this time period, with a sample rate of e.g. 1 minute. The test parameters must also be noted, as these are the conditions under which the performance is measured, and the conditions that must be used for comparison with the performance promised by the manufacturer.

Table 3.1-1: Example of allowable test parameter deviations, suitable for the measurements shown in Figure 3-1. These are the maximum allowable deviations of the measured values from the mean during the test period, for it to be considered as steady-state. The allowable deviations are inspired by ISO 916 and EN 13771.

Parameter	Allowable deviation	Unit
Compressor inlet temperature	± 2	K
Compressor inlet pressure	± 2	%
Compressor speed	± 2	%
Sink inlet temperature	± 2	K
Sink mass flow rate	± 1.5	%
Source inlet temperature	± 2	K
Source mass flow rate	± 1.5	%
Evaporating pressure	± 2	%
Compressor voltage	± 1.5	%
Compressor electrical frequency	± 1	%

Figure 3-1 shows an example of a measurement period from a real process. From this, it is clear to see that the boundary conditions of the HP vary significantly beyond normal measurement uncertainty. The period is quite long, so the deviations are in some cases larger than that specified in Table 3.1-1. The measurements for determining the KPIs of the heat pump could be selected between e.g. 16:00 – 18:00, as this period contains deviations below the allowable maximum deviations.

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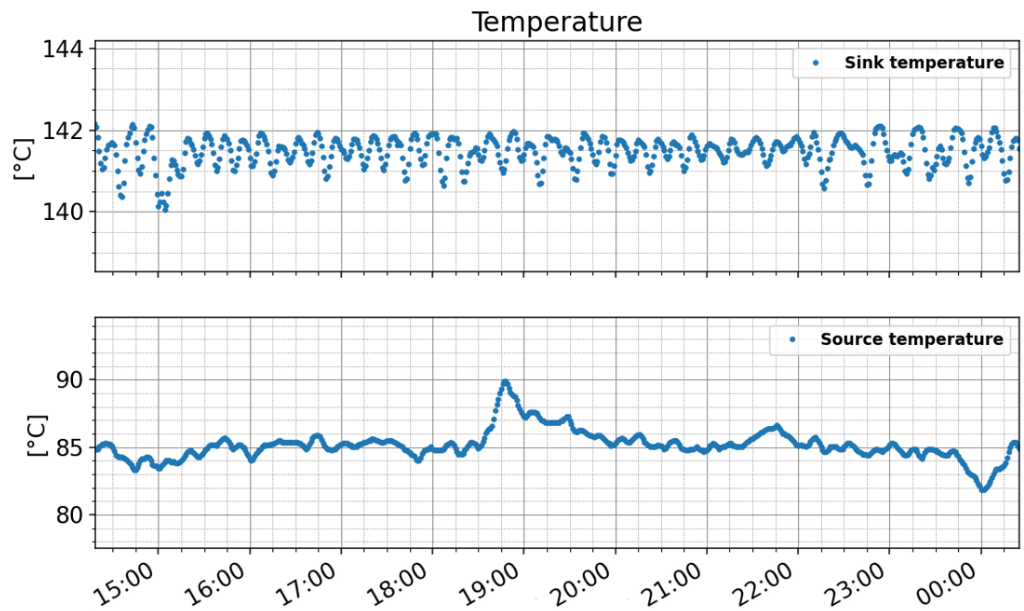

Figure 3-1: Example of variations in boundary conditions with 9 hours of operating data for sink and source inlet temperatures for a HTHP in an industrial heat pump scenario where low-pressure steam is to be produced.

The key measurements of interest may differ depending on the design of the HP. The allowable deviations for a steam generating HP may for example differ from one producing hot water. Here the sink inlet pressure is more relevant than the inlet temperature, as the pressure defines the saturation temperature of the generated steam. For steam with no superheating, the outlet quality must also be measured.

Another example is HPs with water/steam as refrigerant, as these can in many cases be open systems with water injection on the discharge side of the compressor. In this case, the injected water should be included in the sink mass flow rate.

Along with the allowable parameter deviations for accepting steady-state, agreements should also be made upon the maximum measurement uncertainty due to sensor inaccuracy that can be accepted. The values given in Table 3.1-2 are recommended values, these values are considered to cover a 95 % confidence interval. The uncertainty given in the table are deviations from the mean.

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Table 3.1-2: Recommended values of maximum measurement uncertainty to be allowed during the SAT, mainly based on EN 13771-2 (2017) and EN 13141-7 (2021) (*steam flow is measured via the feed water flow).

Measured quantity	**Uncer-tainty**	**Unit**
Absolute pressure	± 1 %	Pa
Refrigerant flow	± 1 %	kg/s
Rotary speed	± 0.07 %	1/min
Temperatures - Temperature for differences (for individually calibrated sensors) - Temperature differences (for calibrated sensor pairs) - Other temperatures	 ± 0.05 K ± 1 % ± 0.3 K	 °C K °C
Electrical quantities - Power - Voltage - Current - Frequency	 ±1 % ±1 % ±1 % ±1 %	 W V A 1/s
Torque	± 1 %	Nm
Water flow	± 1 %	kg/s
Air flow	± 3 %	m^3/s
Steam flow*	± 1 %	kg/s

3.2. Recommended tests

The following list contains further suggestions as to which tests should be made to verify the performance of the HTHP, including the dynamic and off-design behavior:

a) Continuous operation over a longer timeframe at the specified operating conditions (design points) in steady state mode. It can also be considered if the heat pump must be tested at full load only, or if lower capacities also should be tested. It needs to be stressed, that every given test point for SAT and performance tests requires resources, so any unnecessary tests will cost extra without giving any benefits. Part load testing is highly dependent on the application case, and only relevant/possible if the production site allows it. E.g. if another heat supply is able to work in parallel with the heat pump, or if there are times when the production requires lower capacities.

b) Startup and shutdown tests. This includes testing of ramping rates for when the system starts from a long standstill period, and for system startup from standby

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mode where it is pre-heated.

c) Standstill tests: Needs to be included to measure energy losses in the system when not operating.
d) Total testing of at least 30 days is recommended as a “hand-over” test to check for the full availability and functionality of the new heat pump system.
e) Reporting and documentation: Establishment of requirements for comprehensive documentation and reporting of test results must be clarified, including handling of raw data, performance data, and any deviations from the standard testing protocols.
f) Quality assurance and control: Implementation of quality assurance and quality control measures throughout the testing process to minimize errors and ensure the accuracy of the results.
g) Third-Party verification: In some cases, it is recommended to involve third-party verification or certification bodies to validate the test results and ensure impartiality and credibility.

The following list further specifies site test elements that are more “nice-to-have”, i.e., things that are not direct requirements, but can be used to further verify the heat pump performance and optimize the system:

- Oil samples can be taken in predefined intervals for the site testing in order to monitor its quality and to discover potential compressor issues not immediately identified. Oil measurements can e.g. contain information about humidity levels in oil, viscosity, acid level, particles, etc.
- Non-intrusive working fluid flow measurement. This data can be used to validate any simulation models or digital twins that might be created for the project. It can also help with establishing more accurate measurements of the heating capacity.

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3.3. Example case of resulting COP-uncertainty

Given the uncertainties stated in Table 3.1-2, the uncertainty of the calculated COP can be established. An example of this is shown in this section, and is based on inputs from the Task 4 report in the IEA HPT Annex 58 project about HTHPs, see this link:

https://heatpumpingtechnologies.org/annex58/

Information for case example:

Hot water circuit with a flow rate of 10 L/s is heated up from 60 °C to 140 °C. The heating output is measured via a flow meter and two temperature probes, one probe at the sink inlet and one at the sink outlet.

The uncertainties used in this calculation are:

- $\mathrm{u}(\dot{\mathrm{V}}) = \pm 10\,\frac{\mathrm{L}}{\mathrm{s}} \cdot 1\,\% = \pm 0.1\,\frac{\mathrm{L}}{\mathrm{S}} = \pm 0.0001\,\frac{\mathrm{m}^3}{\mathrm{s}}$
- $\mathrm{u}(\mathrm{T_i}) = \pm 0.3\ \mathrm{K}$
- $\mathrm{u}(\mathrm{T_o}) = \pm 0.3\ \mathrm{K}$
- $\mathrm{u}(\mathrm{P}) = \pm \mathrm{P} \cdot 1\,\%$

The heating output is given as:

$$\dot{\mathrm{Q}} = \dot{\mathrm{V}} \cdot \mathrm{c_p} \cdot \rho \cdot (\mathrm{T_o} - \mathrm{T_i})$$

Where $\dot{V}$ is the flow rate, c_p is the specific heat capacity, ρ is the density, T_o is the outlet temperature and T_i is the inlet temperature.

The uncertainty of the heating output is given, using the principle of propagation of uncertainty, as:

$$\mathrm{u}(\dot{\mathrm{Q}}) = \sqrt{\left(\rho \cdot \mathrm{c_p} \cdot (\mathrm{T_o} - \mathrm{T_i})\right)^2 \mathrm{u}(\dot{\mathrm{V}})^2 + (\dot{\mathrm{V}} \cdot \mathrm{c_p} \cdot \rho)^2 \mathrm{u}(\mathrm{T_i})^2 + (-\dot{\mathrm{V}} \cdot \mathrm{c_p} \cdot \rho)^2 \mathrm{u}(\mathrm{T_o})^2}$$

Where $u(x)$ is the uncertainty of the individual measurements. Inserting the respective values yields:

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$$u(\dot{Q}) = \sqrt{\begin{array}{l}\left(1{,}000\,\frac{\mathrm{kg}}{\mathrm{m}^3}\cdot 4{,}200\,\frac{\mathrm{J}}{\mathrm{kgK}}\cdot(140\,°\mathrm{C}-60\,°\mathrm{C})\right)^2\left(0.0001\,\frac{\mathrm{m}^3}{\mathrm{s}}\right)^2 \\ +\left(0.01\,\frac{\mathrm{m}^3}{\mathrm{s}}\cdot 4{,}200\,\frac{\mathrm{J}}{\mathrm{kgK}}\cdot 1{,}000\,\frac{\mathrm{kg}}{\mathrm{m}^3}\right)^2\ (0.3\ \mathrm{K})^2 \\ +(-0.01\,\frac{\mathrm{m}^3}{\mathrm{s}}\cdot 4{,}200\,\frac{\mathrm{J}}{\mathrm{kgK}}\cdot 1{,}000\,\frac{\mathrm{kg}}{\mathrm{m}^3})^2(0.3\ \mathrm{K})^2\end{array}} = \pm\,38.03\ \mathrm{kW}$$

And for the given values the total heating output is:

$$\dot{\mathrm{Q}} = 3360\ \mathrm{kW}$$

The COP is given as:

$$\mathrm{COP} = \frac{\dot{\mathrm{Q}}}{\mathrm{P}}$$

The final uncertainty of the calculated COP is given, again using the principle of propagation of uncertainty, as:

$$\mathrm{u(COP)} = \sqrt{\left(\frac{1}{\mathrm{P}}\cdot \mathrm{u}(\dot{\mathrm{Q}})\right)^2 + \left(-\frac{\dot{\mathrm{Q}}}{\mathrm{P}^2}\cdot \mathrm{u(P)}\right)^2}$$

Since the sensors are assumed to have their uncertainty given for a 95 % confidence interval, there is no need to multiply the uncertainty with a coverage factor. Assuming a COP of 3, the power, P, is 1120 kW. This yields:

$$\mathrm{u(COP)} = \sqrt{\left(\frac{1}{1120\ \mathrm{kW}}\cdot 38.03\ \mathrm{kW}\right)^2 + \left(-\frac{3360\ \mathrm{kW}}{1120\ \mathrm{kW}}\cdot 11.2\ \mathrm{kW}\right)^2} = \pm 0.045$$

Thus, the COP and its uncertainty interval in the given measurement time can be calculated as:

$$\mathrm{COP} = 3.0 \pm 0.045$$

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4. Case studies

This section provides a short description of the three demonstration cases within the SPIRIT project and their process conditions. The applicability of the testing guidelines developed in the previous chapters is discussed for each case. However, since this is a R&D demonstration project a strong focus is here on extended test plans with verification and optimization of the heat pumps in each of the demonstration cases.

4.1. Case 1 – Demonstration at Stella Polaris

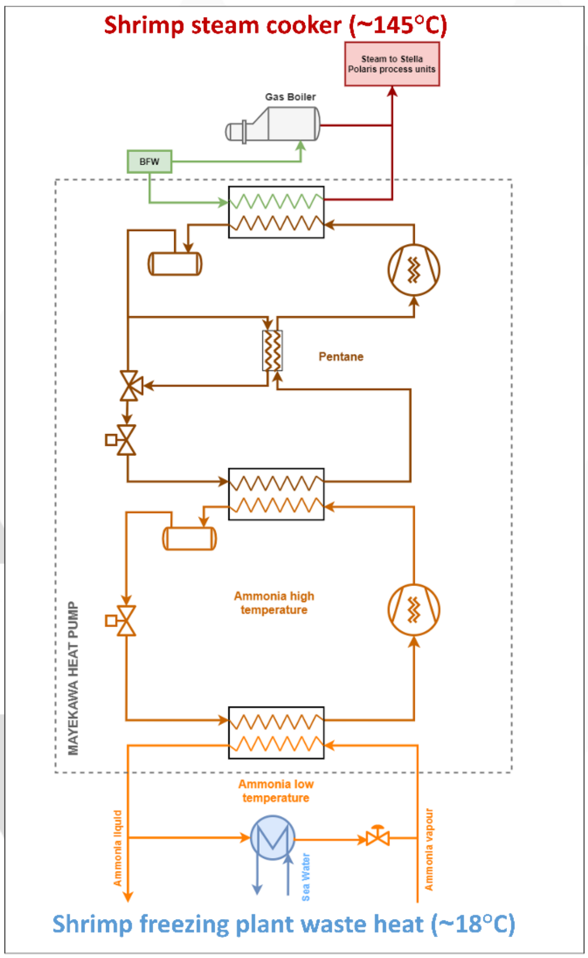

Figure 4-1 Process flow diagram of SPIRIT demonstration case 1.

The Heat Pump consists of a water-to-steam cascade system using two loops with Ammonia/Pentane. The heat source used by the HP is the rejected heat of an Ammonia cooler. The evaporator of the HP is ammonia/ammonia without any intermediate

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loop. The process flow diagram in Figure 4-1 shows how the heat pump is integrated in the plant.

Operation pattern

The HTHP operation is fluctuating in an ON/OFF pattern of approximately 2 weeks/1 day.

Heat source side:
The heat source is defined by the NH_3 refrigeration cycle from the existing cooling system. Therefore, the temperature is also defined by this loop. On the heat source side, very limited controlled variations of the operating conditions can be performed.

- Fluid: Ammonia
- Temperature: 18 – 23 °C
- Pressure: 8 bar-a

Heat sink side:
If the steam boiler (gas) is operated in parallel with the heat pump, then the heating capacity in the sink side of the HTHP can be varied. This could be done by changing the speed of the compressors. When this happens, the flow rate of both loops (MT, HT) changes. This could affect the pinch temperatures in the source and sink heat exchangers.
The heat sink is the steam generation driven to the prawn cooker. The Prawn cooker requires to maintain its internal temperature at approx. 100 °C. This is achieved by the pressure and temperature maintained within the Prawn cooker. A PCV controls the pressure of the steam at the steam outlet of the Prawn cooker. For the heat pump side, the steam pressure is controlled by another PCV, which is set at the required pressure of the steam network (3.15 barg).

- Fluid: BFW/Steam
- Temperature: 172 – 150 °C
- Pressure: 4.15 bar-a

Heat generation & power consumption

The HP will generate steam at approximately 700 kW, and the used combined power (2 compressors) is estimated to be approx. 382 kW (400 V, 50 Hz).

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Application of testing guidelines

The measurement campaigns consist of two types covering short-term variable operation and long-term stable operation. This testing program is planned in a manner that the SP process plant is not affected in a way that could have an impact on the product and/or in its standards.

The short-term tests will cover the following investigations, with focus on part-load testing and optimizations:

- Transient operation: Achieved during ramp-up/down by varying the compressors speed.
- Optimization of the intermediate heat exchanger saturation temperature in a range between 75 °C and 90 °C.
- Part load operation: While on the source side very limited controlled variations of the operating conditions can be performed, the capacity on the on the sink side can be regulated by changing the speed of the compressors.

The stability of the operation and performance during long-term testing will be evaluated by using statistical methods such as calculating the variance and coefficient of variation for the recommended key parameters to measure.

Other testing parameters that will be included

Further testing parameters consists of the following:

- Variation of the RPM of the compressors. This will result in changes in thermal capacity, intermediate condensation/evaporation temperature, mass flow rate, and ΔT in the heat exchangers. This can also give a curve of the compressors' performance (i.e. volumetric and isentropic efficiency of the compressor).
- Variation of the oil cooling temperature, which is recovered in the steam loop. This modification will affect the steam loop. An alternative within this same system is to investigate different oil temperatures, which will affect the performance of the compressors and therefore the heat pump.
- Variation of steam pressure via the steam pressure control valve (PCV). By changing the set point of the pressure control valve.

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4.2. Case 2 – Demonstration at Tiense Suiker

The overall system design for this system can be seen in Figure 4-2.

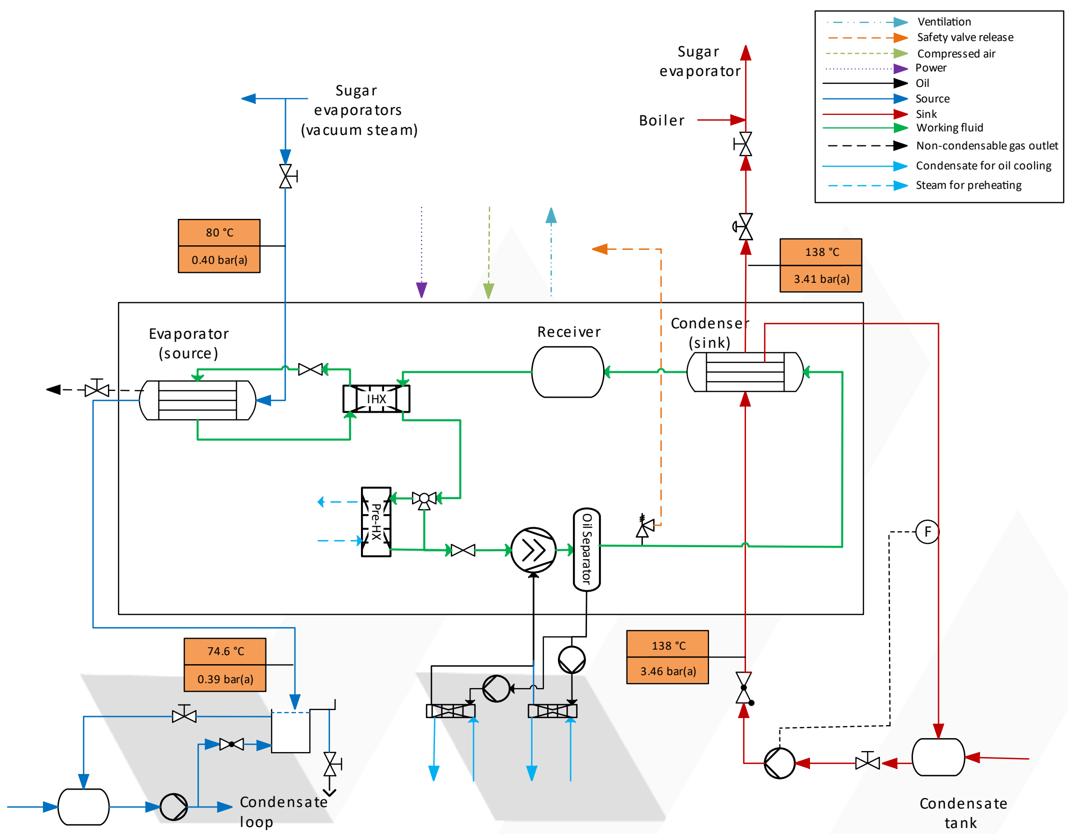

Figure 4-2: Process flow diagram of SPIRIT demonstration case 2.

The heat pump is a steam-generating cascade system, with the heat source being low pressure steam from the end of the sugar-extraction process. The generated steam is at 1.7 or 3.5 bar(a) (114 or 138 °C sat. temp.) for the 'thick juice' and 'beet' production campaign, respectively, and the source steam is around 0.4 bar(a) (76 °C sat. temp.) during all campaigns. The beet campaign is the main production campaign and is thus selected as the design point. There are no intermediate loops between the HP and the source/sink. The 'pre-HX' indicated in Figure 4-2 is can be used during startup to ensure sufficient superheating of the suction gas.

The heat source is vacuum steam returned from the end of the process and therefore the conditions cannot be regulated. The heat source conditions are listed below:

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- Fluid: Steam
- Temperature: 80 °C
- Pressure: 0.4 bar-a
- Heat transfer rate: 2.6 MW / 3.5 MW (thick juice / beet campaign)

The sink side conditions are also partially dictated by the process, but higher sink pressures and temperatures can be achieved with a pressure control valve. The sink conditions during normal operation are listed below:

- Fluid: Water
- Temperature: 114 °C / 138 °C (thick juice / beet campaign)
- Pressure: 1.7 bar-a / 3.5 bar-a (thick juice / beet campaign)
- Heat transfer rate: 4.2 MW / 3.6 MW (thick juice / beet campaign)

Figure 4-3 shows measured temperatures and pressures which will be used for the sink and source sides in a selected period of a previous beet campaign.

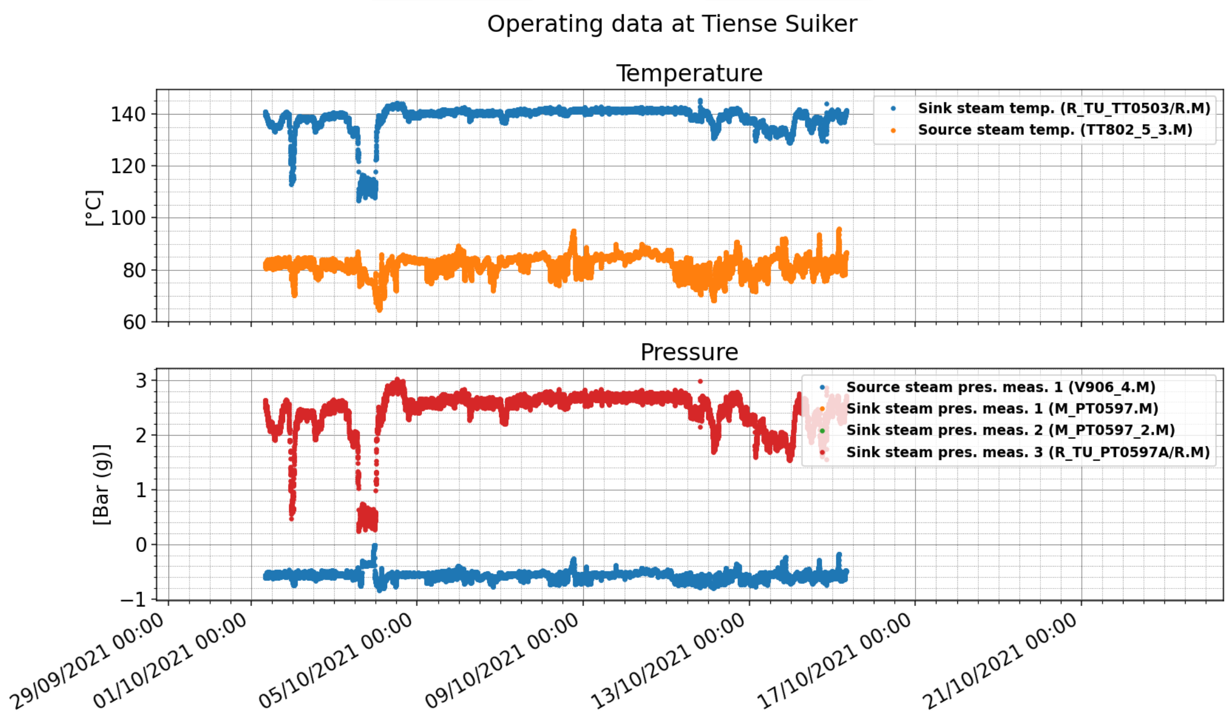

Figure 4-3: Example of expected the sink and source temperature and pressure during the beet campaign.

Figure 4-4 shows the measured temperatures and pressures at the sink inlet and outlet in a selected period of the thick juice campaign.

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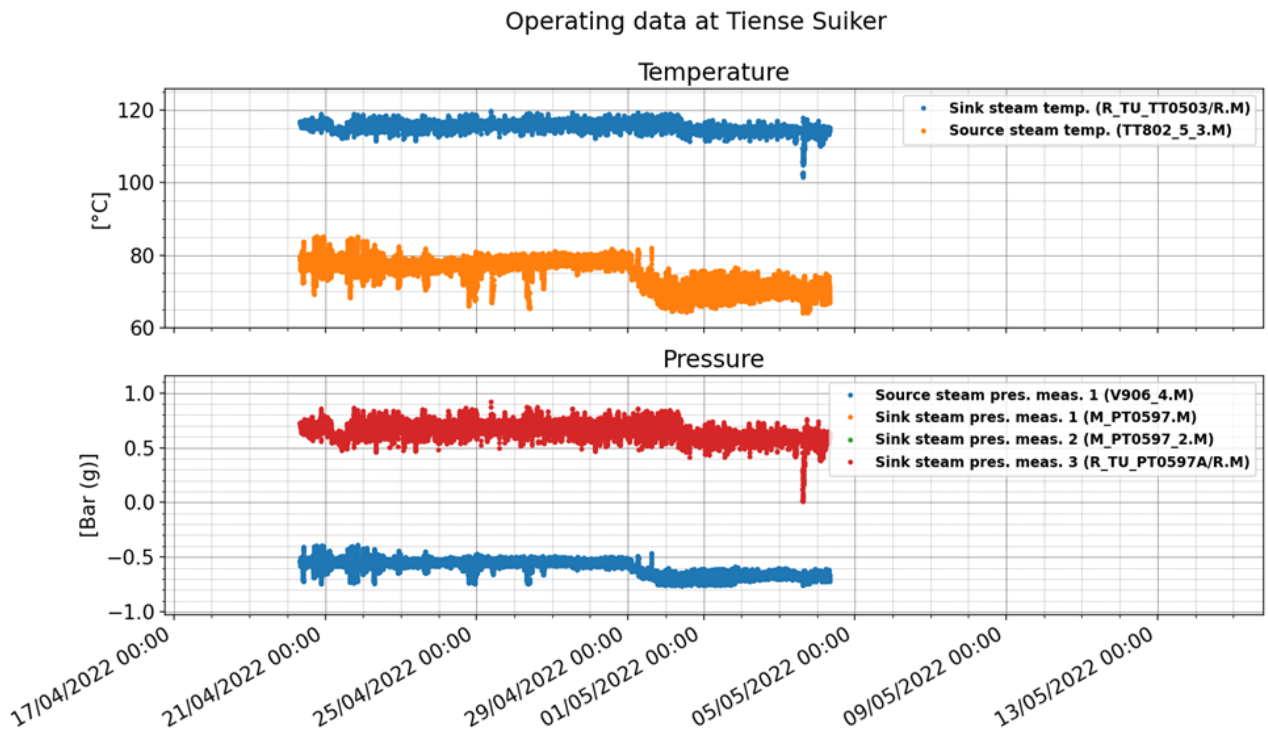

Figure 4-4: Sample of the sink and source temperature and pressure during the thick juice campaign.

The average and standard deviation values of the sink and source temperature and pressures are reported in Table 4.2-1.

Table 4.2-1: Average values and standard deviations for each production campaign

Campaign	Source in temperature	Source in pressure	Sink out temperature	Sink out pressure
Beet campaign	Avg: 82.2 °C Std: 3.5 °C	Avg: -0.57 bar(g) Std: 0.07 bar(g)	Avg: 137.6 °C Std: 3.3 °C	Avg: 2.29 bar(g) Std: 0.30 bar(g)
Thick juice campaign	Avg: 74.5 °C Std: 4.2 °C	Avg: -0.60 bar(g) Std: 0.07 bar(g)	Avg: 115.7 °C Std: 1.3 °C	Avg: 0.66 bar(g) Std: 0.07 bar(g)

Application of testing guidelines

The tests will be performed during the production campaigns of the sugar plant because there are no plans to install the piping necessary to operate the HTHP independently of the plant.

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As recommended, the testing program includes long-term tests that aim to verify the heat pump stability and robustness, and short-term tests of variable operating conditions.

Full load tests: The temperature and pressure on the source side are dictated by the process and it is not possible to regulate them. On the other hand, a pressure control valve will be installed on the sink side after the HTHP, allowing higher sink pressures (and therefore higher sink temperatures). Therefore, the testing will cover different sink temperatures.

Partial load tests: The HTHP supplies only a fraction of the heat demand of the process because it works in parallel with a boiler that supplies the rest of the heat demand. Therefore, the heat pump will normally be operated at maximum capacity, but it will also be operated at part load during the part load testing where the compressor capacity can be reduced up to 50 % (the compressor speed can be regulated from 1500 to 3600 RPM).

Ramp-up and ramp-down tests will also be made. The tests will also be used to determine the potential required flow for startup internal heat exchanger.

From Table 4.2-1 it can be seen that the standard deviation of the sink outlet pressure during the beet campaign is quite high, at 0.30 bar relative to the mean value of 3.29 bar(a). This is very relevant to know during the on-site testing, as this represents a ±3 K difference in saturation temperature. It is thus important to identify periods with lower deviations, when performing measurements to verify the performance of the heat pump.

Since the heat pump both generates steam in the sink and condenses water in the source, it is important to measure the saturation temperature on both sides, as this is the temperature at which most of the energy is transferred.

The steam generating HEX on the sink side features an over-circulation, such that the flow into the HEX is not the full flow that is evaporated. When calculating the heating output, it is thus important to measure both the flow into the HEX and the flow being circulated out of the HEX and subtracting the two from each other to get the evaporated flow.

Other testing parameters

This will include the following:

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- Oil samples: Determine the oil quality every 500 hours of operation using a sample taken after startup as a reference.
- Refrigerant flow rate measurements: To generate data for modelling the digital twin
- Optimization of oil temperature, VI slider position, condensation temperature: determine optimal values that lead to highest efficiency
- Noise level: Sound measurements to verify that sound requirements are met
- Vibration level: Vibration measurements to verify that the vibration requirements are met

4.3. Case 3 – Demonstration at Smurfit Kappa

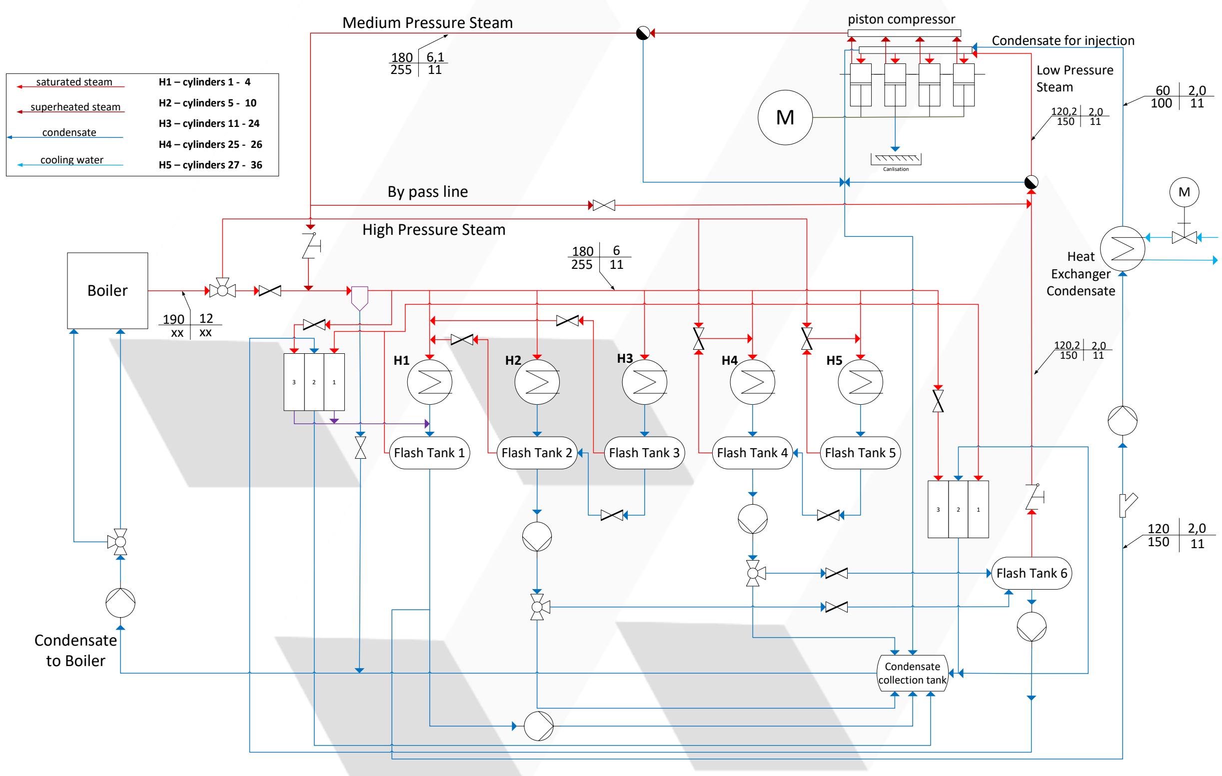

Figure 4-5: Process flow diagram of SPIRIT demonstration case 3.

In the third demonstration case, the end-user is a paper production plant. A mechanical vapor recompression heat pump is used to raise the pressure of steam used for the paper drying process.

The process flow diagram is shown in Figure 4-5. The steam is fed into the process at a pressure of 6 bar(a) and a temperature of around 180 °C and heats the cylinders H1, H2, H3, H4, H5 for paper drying. The pressure at the inlet of each cylinder varies

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according to the process requirements. Figure 4-6 shows the steam pressure at the common inlet to the paper machines and at the inlet of four different cylinders (H5, H3, H2, H1) measured during a selected period of the plant operation.

After the drying process, the steam condenses completely. The condensate is collected in a flash tank (Flash Tank 6) where it is expanded to 2 bar(a). The flash steam is then recompressed and refed into the process.

A condensate injection line is implemented to adjust the temperature of the steam during compression. The condensate is taken from one of the flash tanks (Flash Tank 1) and cooled down by a heat exchanger.

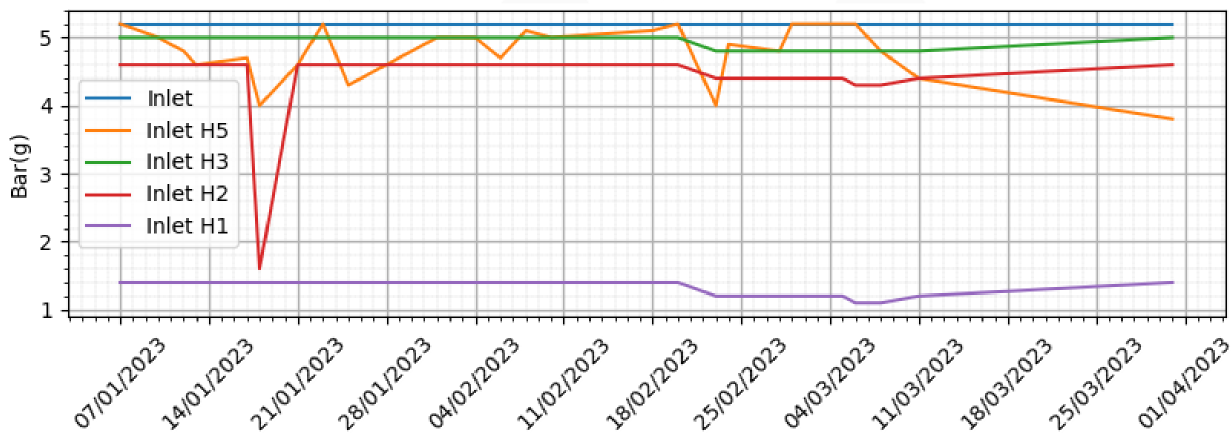

Figure 4-6: Sample of the steam pressure at the common at the inlet of the individual paper machines H5, H3, H2, and H1.

Operation pattern

24h operation cycle, 7 days per week.

Separator (Flash Tank 6) outlet / compressor inlet:

The compressor is connected to the process through a separator (Flash Tank 6). The purpose of the separator is to throttle the condensate coming from different drying cylinders to the same pressure level. The amount of condensate from the drying cylinders to Flash Tank 6 is regulated by a three-way valve. The nominal operating conditions are listed below:

- Fluid: Steam (two-phase)
- Temperature: 120.2 °C
- Pressure: 2.0 bar-a
- Mass flow rate: 800 kg/h

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Heat generation & power consumption:

The compressor will deliver 0.7 MW of heat.

Application of testing guidelines:

The regular operation mode of the compressor, used as the main case for testing, is "inlet pressure controlled". The compressor keeps the inlet pressure level constant at 2 bar(a), by adjusting its speed (and thereby its mass flow rate) within its control range from 0.35 to 1.00 t/h. Deviations in inlet pressure are not expected as the inlet pressure control system is expected to regulate the pressure fast and precisely.

The pressure level of the high-pressure steam is controlled by the boiler operating in parallel, supplying the difference between the steam demand and the steam produced by the compressor, and kept constant to 6 bar(a).

Besides the regular operation mode, the part load operation (250-1000 kg/h) will be tested to estimate the electrical power demand and COP as a function of the steam mass flow rate. When in part load operation, the inlet pressure will be controlled by regulating the flow to the compressor (by closing the 3-way valve from Separator 2 and 4 stopping part of the condensate flow to Separator 6 and/or by supplying additional steam from a bypass line).

Furthermore, it is planned to vary the inlet pressure (between 1.8 and 2.5 bar absolute) and outlet pressure (between 6.1 and 6.5 bar absolute) for the nominal and part load operation cases, to estimate electrical power demand and COP as a function of the compression ratio.

To achieve steady-state operation during measurement periods, it is important to keep the steam demand as constant as possible, such that the compressor operates at constant speed. The maximum allowable deviations in compressor speed must be assessed relative to what is possible on-site.

As recommeded in the guidelines, since this is an open system where injection water is included, it is important to include this in the mass flow and look at the enthalpy change of the injected water, when calculating the heating output. The inlet and outlet pressures and temperatures are of course also important to determine the pressure lift and level of superheating at the discharge, and in turn also the heating output.

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