LAUNCH AND FIRST EXPERIMENTAL RESULTS OF A REVERSIBLE HEAT PUMP-ORC PILOT PLANT AS CARNOT BATTERY

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ABSTRACT

Carnot Batteries are a promising approach to store electrical energy in base-load scale. To study the reversible combination of a heat pump cycle and an organic Rankine cycle as Carnot Battery a pilot plant was designed, constructed and launched. With a designed power consumption of 15 kW_{el} at the HP-compressor, a power generation of 9 kW_{el} at the ORC-expander and a storage capacity of 270 kWh_{th} the pilot plant allows predictions for big scale application of the technology already. It enables a steady state operation over several hours of charging and discharging as well as a closer look at start-up behavior and part-load issues. The operation brings new insight at the previous considerations regarding reversible use. This paper shows the launch of the pilot plant and gives the first experimental results. It summarizes the design aspects and evaluates them with experimental data to close the gap between theoretical studies and industry scale solutions. The experiments showed the working fluid collector vessel has a positive influence on stabilizing the heat pump process and adapting to the ORC process. The behavior of the lubrication oil flow is depending on several operation properties. The non-stationary start-up of both operation modes and the interaction of several process parameters are presented.

1 INTRODUCTION

Facing the challenges of renewable energies' fluctuating power generation the Carnot Battery is an emerging storage technology (Steinmann *et al.*, 2019). In times of surplus energy, a power-to-heat cycle loads a thermal storage, which can be unloaded applying a heat-to-power cycle in case of need. While many different processes are discussed for the charging and for the power generation step (Dumont *et al.*, 2020a), a research group at the Energy Campus Nuremberg (EnCN) focuses on a reversible heat pump - organic Rankine cycle (HP-ORC) as Staub *et al.* (2018) presented (figure 1). This approach combines the two related processes to use components reversibly and save investment costs as a result (Frate *et al.*, 2020). A major part of the research project is the design, built-up and operation of such a reversible HP-ORC pilot plant to contribute to the ongoing international research, which process simulation and other theoretical studies still dominate.

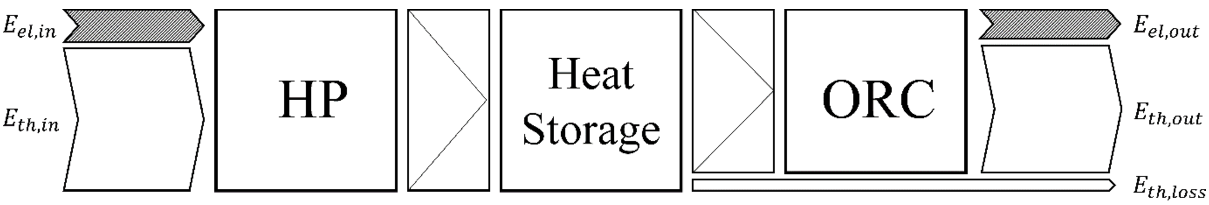

Figure 1: Concept of a Carnot Battery with heat pump and organic Rankine cycle

There is similar experimental research going on by Dumont and Lemort (2020b) studying a Carnot Battery pilot plant using a scroll machine. The reversible heat pump – organic Rankine cycle pilot plant described in this paper uses a reversible screw machine with an upper (storage) temperature level of up to 120 °C. Thus, the pilot plant will help to improve the knowledge of reversible use of components (especially of screw machines) in the given context as well as evaluate aspects of the reversible combination of two processes in general. Special features of the pilot plant are the internal heat exchanger, the reversible oil separator and the working fluid collector.

2 METHODS AND MATERIAL

2.1 Overview of the reversible HP-ORC

Already during the sketch of the pilot plant, the reversible combination of a heat pump process and an ORC requires an innovative strategy. Especially the reversible use of heat exchangers (condenser and evaporator) and of the compressor-expander-unit had a special attention.
Steger *et al.* (2020a) and Eppinger *et al.* (2021) explained the design of the reversible HP- ORC pilot plant in detail. In the following just an overview of the pilot plant is given. Figure 2 shows a simplified piping and instrumentation diagram (P&ID) of the main part of the pilot plant (reversible combined cycle). Two heat exchangers connect the HP-ORC process with the auxiliary service lines (cooling/heating circuits (C/H), storage circuit).

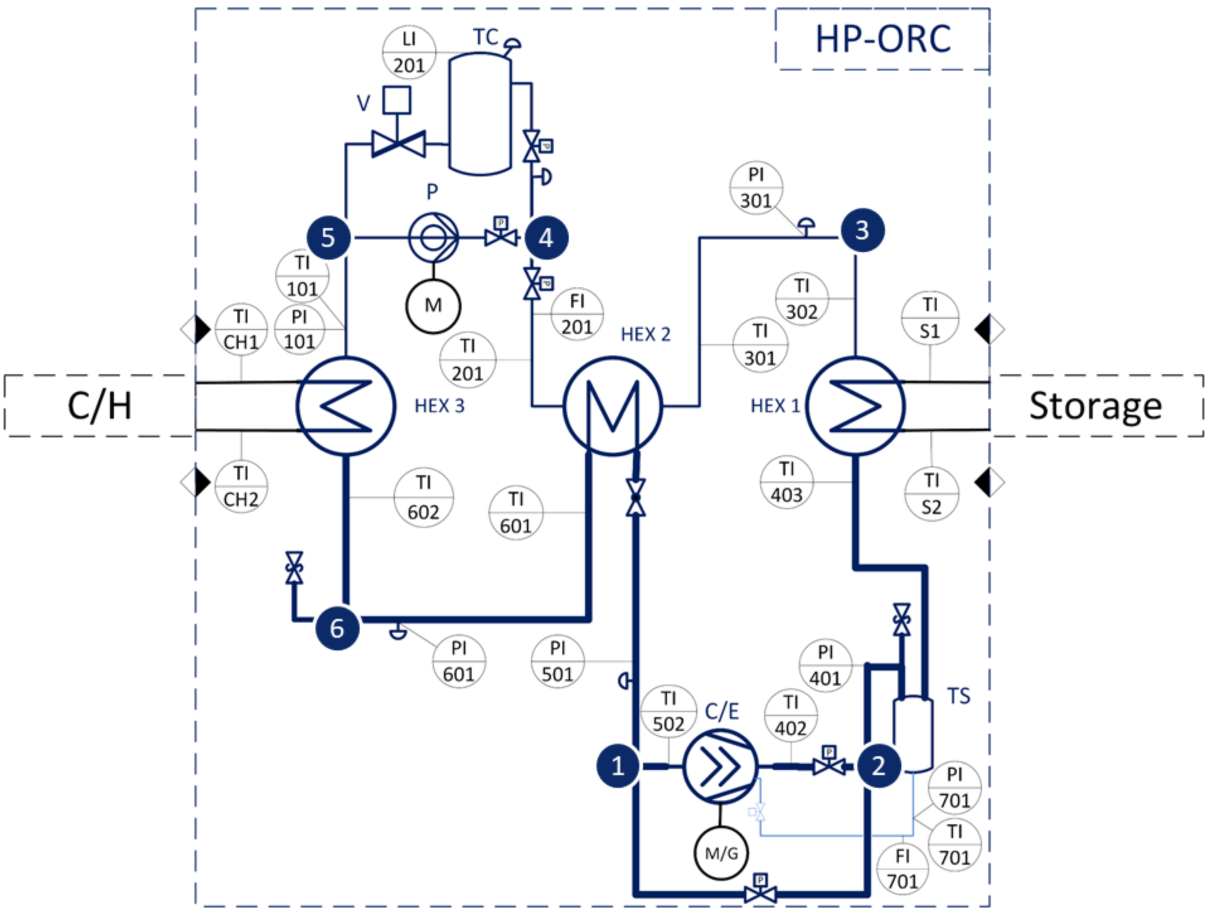

Figure 2: Simplified P&ID of the reversible HP-ORC (numbers in the circle refer to condition points)

The reversible cycle, using R1233zd(E) as working fluid, consists of an upper (HEX1) and a lower (HEX3) chopper brazed plate heat exchanger, which work both as evaporator and as condenser according to the operation mode. Another internal vapour-liquid heat exchanger improves the efficiency (HEX2). There is a screw-machine (C/E) on the vapour side, which can work reversibly as HP-compressor or ORC-expander. On the liquid side, there are the HP-throttle valve (V, pneumatic needle valve) and the ORC-pump (P, vertical centrifugal pump). The fluid collector vessel (tank collector, TC) and the reversible oil separator (tank separator, TS) are two further features with a special function in the reversible cycle: The collector vessel balances the amount of working fluid in the processes, especially during a change of operation mode. The reversible oil separator works in both directions to supply the reversible machine in compressor as well as in expander mode with a special ester (POE) synthetic refrigeration oil. The pilot plant is equipped with several sensors and actors. The speed of the compressor and of the pump can be adjusted manually. The speed of the expander adapts to a given torque limit.

2.2 Boundary conditions

The current paper summarizes the first experimental results from the operation of the reversible HP-ORC pilot plant. The publication wants to share already the early results to the research community even though the plant will be further modified. Concerning these first experiments, there is no insulation installed yet, and the storage is realized as an auxiliary water cycle so far. Each diagram shows one run in total or in parts, but they are carefully selected to represent the general experiences of the particular case. The boundary conditions are different for the operation modes and are given by table 1, and table 2:

Table 1: Boundary conditions HP mode

value	amount
heat source temperature	50 °C
heat source volume flow	150 l/min
storage volume flow	8.3 l/min
throttle valve opening	83 %
Screw compressor speed	0 … 1500 rpm

Table 2: Boundary conditions ORC mode

value	amount
storage upper temperature	95 °C
Cooling water temperature	19.2 °C
Cooling water volume flow	54.6 l/min
ORC pump speed	0 … 2500 rpm
Screw expander speed	0 …-2000 rpm

2.3 Evaluation methods

The programmable logic controller (PLC) records the sensor data with an interval of two seconds. The data is further processed using python libraries NumPy (Harris *et al.*, 2020), pandas (The pandas development team, 2020), Matplotlib (Hunter, 2007) and CoolProp (Bell *et al.*, 2014).

3 FINDINGS FROM FIRST EXPERIMENTAL STUDIES

3.1 HP operation mode

The experimental start-up of the pilot plant in HP mode begins with the pre-heating of the artificial heat source and crucial parts of the plant such as the bottom of the oil separator. The throttle valve is fixed to a certain value and is not changed until full load is reached. A potential instability of the non-stationary start-up process is thereby avoided. The speed of the compressor is then increased in discrete steps as figure 3 shows. Furthermore, the power at the waste heat source, at the storage and the screw are displayed in addition to the coefficient of performance (COP) of the heat pump cycle during start-up.

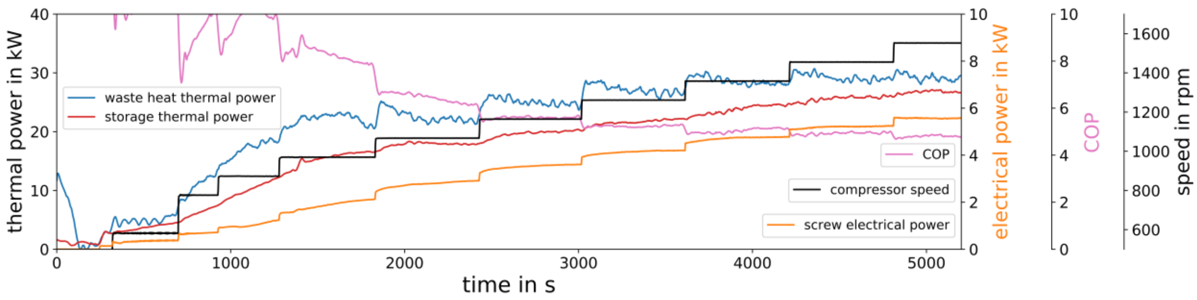

Figure 3: Power and COP during start-up of HP mode

Figure 3 shows the amount of power increasing with the speed of the compressor. The COP starts at a high level because of a low compression end temperature but balances at a value of about 4.5 when reaching the desired operation point.

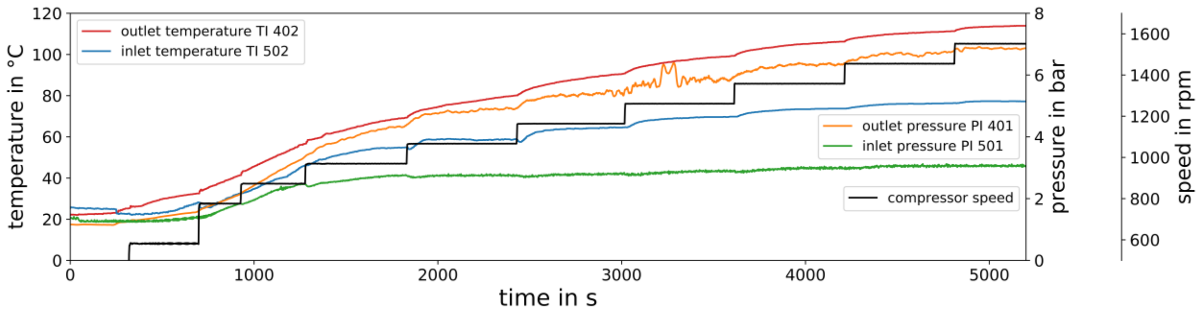

Figure 4: Temperatures and pressures during start-up of HP mode

In figure 4 the temperatures and pressures upstream (compressor inlet, TI 502 and PI 501) and downstream (compressor outlet, TI 402 and PI 401) of the machine are shown. The outlet temperature and pressure increase with the compressor speed. In a similar way, the inlet temperature increases, while the inlet pressure hardly rises.

3.2 ORC operation mode

Starting up the reversible cycle in ORC mode requires another procedure. After heating up the relevant parts (heat exchangers, oil separator bottom), the ORC pump circulates the working fluid to increase its temperature. The screw machine is motor driven at a low speed. If needed, working fluid is injected from the fluid collector (see 3.4 Operation with the working fluid collector vessel). In several steps, the speed of the ORC pump is increased. Figure 5 shows the power at the heat exchangers (cooling and storage) and of the ORC pump and the screw expander. Moreover, the efficiency of the organic Rankine cycle (ORC pump included) and the speed of the ORC pump and the screw expander are given.

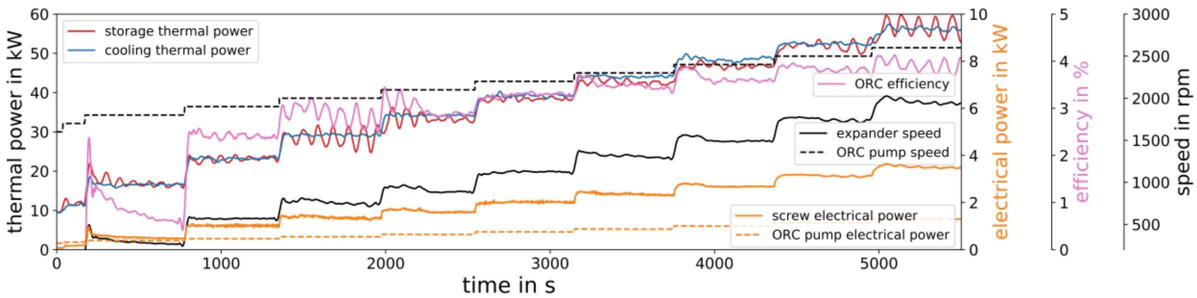

Figure 5: Power and efficiency during start-up of ORC mode

From a certain point on (t = 200 s), the speed of the ORC pump is sufficient to increase the volume flow and the pressure of the working fluid to a level at which the screw machine changes from motoric to generator mode. The speed of the expander adapts according to the manually given torque limit of 17.15 Nm. With increasing speed of the ORC pump, the expander speed and the powers at the heat exchangers and the machines increase as well, resulting in an efficiency of about 4 % at the desired operation point. In the range 1500 s < t < 2300 s and 4900 s < t < 5500 s the storage auxiliary water cycle causes a fluctuating power output translating this effect directly to the efficiency.

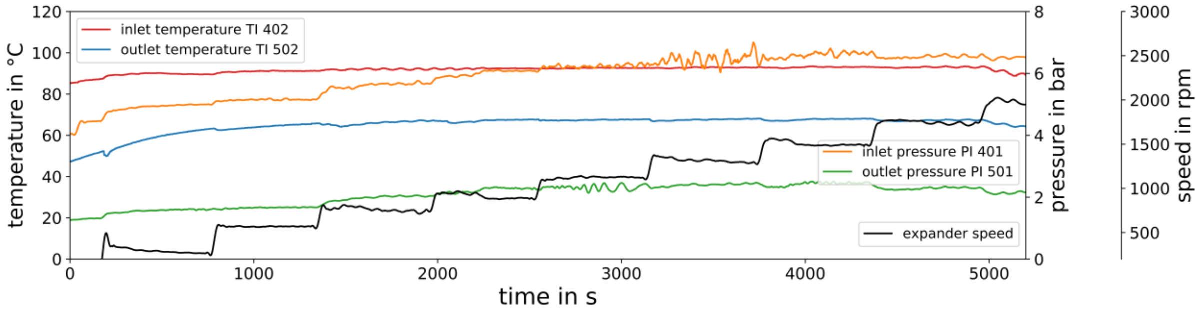

Figure 6: Temperatures and pressures during start-up of ORC mode

In figure 6 the temperatures and pressures upstream (expander inlet, TI 402 and PI 401) and downstream (expander outlet, TI 502 and PI 501) of the machine are shown. Due to the manually fixed temperature levels of hot and cold side, the temperatures at inlet and outlet do not change too much. The expander inlet pressure level rises because of the increasing ORC-pump speed.

3.3 Overview of both processes

Figure 7 shows the temperature-entropy-diagrams of both processes at stationary operation points (HP: at t = 5000 s in figure 3; ORC: at t = 5500 s in figure 5). The state points refer to those of the P&ID in figure 2. The heat source (ORC: upper line, HP: lower line) and sink (ORC: lower line, HP: upper line) are indicated with green lines.

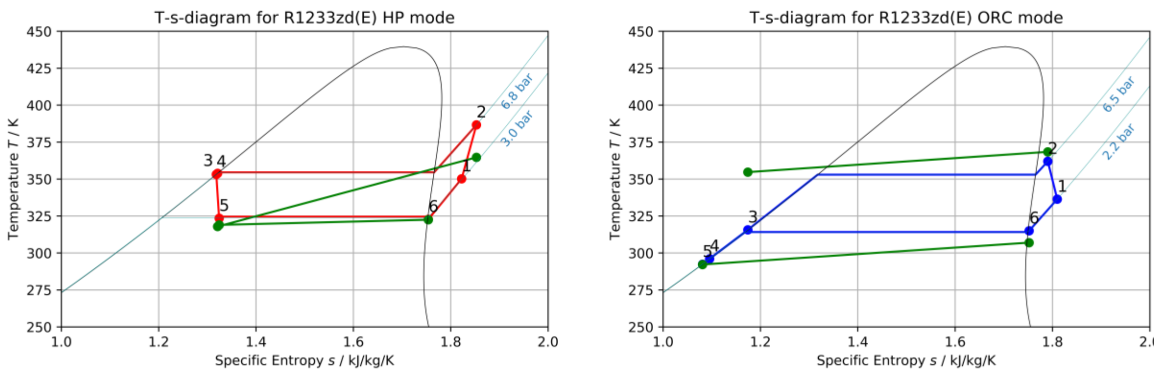

Figure 7: Temperature-entropy-diagrams for HP mode (left, red) and ORC mode (right, blue); heat source/sink in green

The heat pump cycle operates at a low-pressure level of 3.0 bar and a high-pressure level of 6.8 bar. The refrigerant mass flow is about 230 g/s at this point. The organic Rankine cycle works with a low pressure of 2.2 bar and a high pressure of 6.5 bar. The refrigerant mass flow in the ORC mode is about -270 g/s. The diagrams show that the high-pressure reversible evaporator-condenser (HEX1) works in both modes (HP: 2-3, ORC: 3-2). HEX3, the low-pressure ORC-condenser (6-5) and the low-pressure HP-evaporator (5-6) has also a good performance in HP and ORC mode. The internal heat exchanger (HEX2) is meant to shift power from the vapor to the liquid side and increase the efficiency of both

processes through this. While in ORC operation mode the device seems to work well (1-6 and 4-3), in HP mode another aspect plays a role here: It is assumed that the HP condensation is not finished in the condenser HEX1 but also takes place in the internal heat exchanger HEX2. The position of point 4 in the T-s-diagram cannot be measured experimentally, but is most likely within the two-phase range. This aspect will be studied further after upgrading the pressure sensors at this point of the cycle.
Table 3 shows an overview of the main process parameters of the heat pump cycle and the organic Rankine cycle at the stationary operation points. Both processes operate at a similar upper temperature according to the storage behaviour. The power of the ORC-expander was lower than the power of the HP-compressor. There is additional headroom regarding the machine power, as it is designed for up to 15 kW_{el} (HP) and 9 kW_{el} (ORC). The upper temperature level in HP mode reaches 108.4 °C, the inlet temperature of the screw expander is about 88.7 °C. The processes reach a performance of COP 4.95 (HP) and 3.88 % (ORC). Further improvements to the pilot plant and adjustments to the temperature levels will most likely increase the performance.

Table 3: Overview of process parameters

value	**HP mode**	**ORC mode**
Electrical power screw	5.041 kW	-3.502 kW
Electrical power ORC pump	-	1.301 kW
Thermal power HEX 1	-24.921 kW	56.725 kW
Upper temperature level screw	108.4 °C	88.7 °C
Lower temperature level screw	71.7 °C	63.6 °C
Upper pressure level screw	6.10 bar(a)	6.53 bar(a)
Lower pressure level screw	2.74 bar(a)	2.18 bar(a)
HP Coefficient of Performance (COP)	4.95	-
ORC efficiency	-	3.88 %

3.4 Operation with the working fluid collector vessel

A fluid collector vessel is common in larger heat pump applications to adapt the amount of refrigerant in the cycle to the current load (Linck and Giebe, 1999). The reversible combination of two cycles enhances the differences in fluid mass as the pressure, temperature and density at the apparatuses vary from operation point to operation point. During design of the pilot plant, it was not completely clear how and to which point the level of the fluid collector vessel can or must be manually adapted. Figure 8 shows the level of the collector during change of load of the compressor.

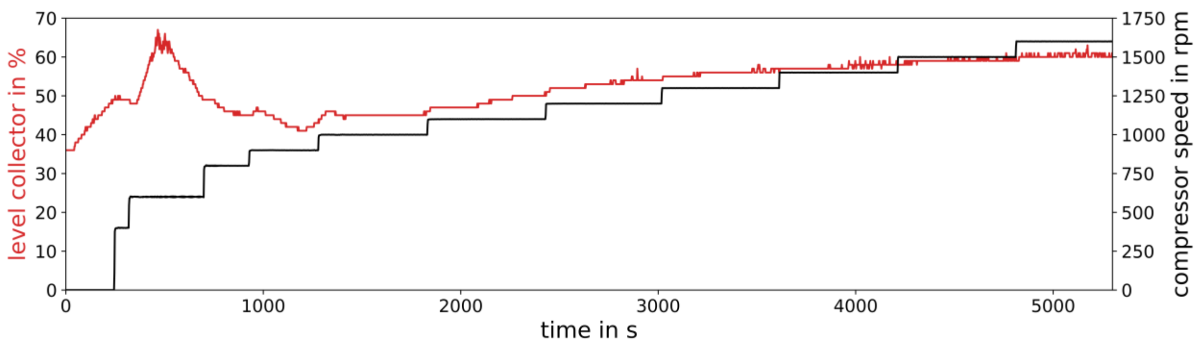

Figure 8: Level of the working fluid collector vessel in HP mode

The experimental results show that the level of the collector changes with every change in operation. Especially rapid rises of the compressor speed result in a sudden increase of the level. After a while, this overshooting declines reaching a steady state level. During operation, this constant level in the fluid collector vessel turned out to be a good indicator for accomplishing a steady state of the heat pump cycle.

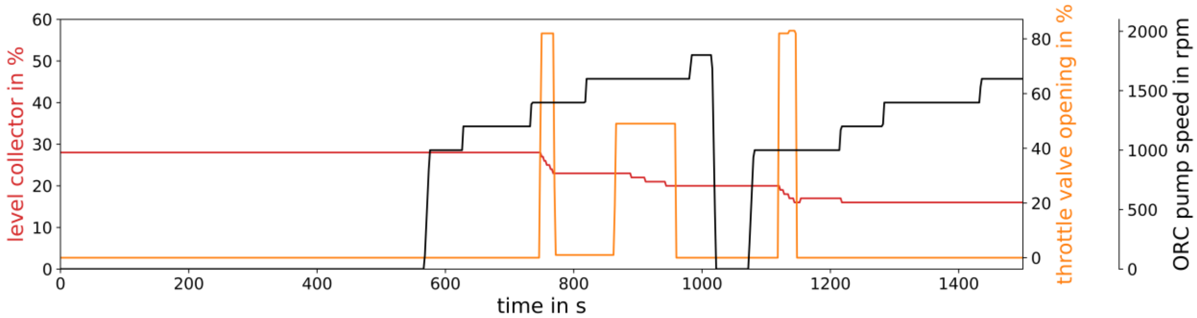

Figure 9: Level of the working fluid collector vessel in ORC mode

The fluid collector vessel is a crucial part not only in a heat pump cycle systems but also in organic Rankine cycle systems, as Dickes *et al.* (2020) explained. Thus, it can be used to change the amount of working fluid in ORC mode without opening the cycle. Like in HP mode, the mass of working fluid in the apparatuses change according to the operation point. Additionally, after switching from HP mode to ORC mode, the apparatuses are still filled with the certain amount of fluid corresponding to the earlier HP mode. Thus, the fluid collector vessel is mainly important short after changing the operation mode. Figure 9 shows, how the ORC pump can be used to suck working fluid from the collector vessel, when the HP throttle valve is opened. The amount of the transferred working fluid is indicated via the collector vessel's fluid level. Conversely, surplus working fluid can be fed back in the collector, if the operation requires doing so.

3.5 Oil flow and its dependencies

The used twin-screw machine works most efficient when lubricated (Wu *et al.*, 2017). The optimal way to do this in both reversible operation modes has been considered in the previous planning process, leading to the position of the oil separator at the high-pressure side of the machine (Steger *et al.*, 2020b). To monitor and study the oil supply in the pilot plant a closer look at the pressure and temperature of the oil after the separator is useful. The oil supply can be observed via an inspection glass. Figure 10 shows the non-stationary start-up of the heat pump process. The oil pressure (PI 701) is highly depending on the suction (PI 501) and discharge pressure (PI 401) of the screw machine. A sufficient oil supply takes place, if the oil pressure level is in between, experiences from the first test runs have shown.

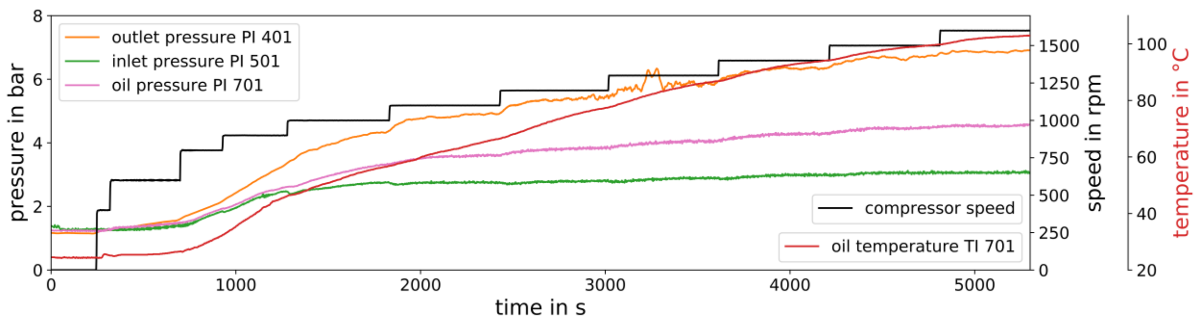

Figure 10: Lubrication in HP mode

Figure 11 shows the corresponding diagram for the start-up of the organic Rankine cycle. Here the oil pressure (PI 701) resides slightly over the outlet pressure of the expander (PI 501). The oil flow according to the observations at the inspection glass was sufficient during the measurements. Thus, the reversible usage of the selected symmetrical bi-directional oil separator is proofed. A needle valve (moved by a float switch according to the oil level) opens and closes the oil separator's sink. When the needle valve closes, the oil flow stops and the oil temperature drops. Such a periodic opening and closing of the oil separator sink can be assumed looking at the oil temperature at 2000 s < t < 2700 s. This might be an indication for an insufficient amount of oil filling.

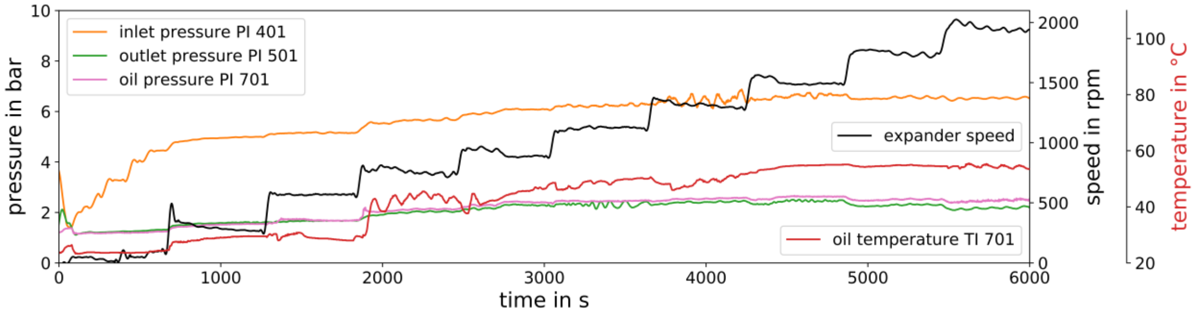

Figure 11: Lubrication in ORC mode

4 CONCLUSION AND OUTLOOK

The findings from the first experimental test of the reversible HP-ORC pilot plant can be concluded as follows:

- The reversible operation of a combined HP-ORC-pilot plant is studied
- The start-up behavior of both processes of the reversible cycle are shown
- The reversible usage of a screw machine as HP-compressor and ORC-expander has been proved experimentally
- The reversible usage of a combined HP-condenser and ORC-evaporator has been proved experimentally
- The working fluid collector is a helpful apparatus to balance the working fluid mass in HP mode as well as in ORC mode
- The reversible usage of a bi-directional oil separator has been proved experimentally

The pilot plant will be further improved according to the findings of the first runs. A device to regulate the oil filling in the separator without opening the cycle to the environment will be added. Furthermore, several pressure sensors will be installed to observe crucial process steps such as the phase change in the condenser and evaporator. Moreover, the pilot plant will be insulated; therefore, a performance improvement is expected. Through the coupling with the hot water storage tank replacing the auxiliary water cycle additional findings about the loading and unloading behavior of a Carnot Battery are expected. Following these modifications, further experiments will focus on the different aspects of the cycles in detail. Long-term runs, experiments at higher temperatures and a coupling with the pilot-scale water heat storage are scheduled. Finally, the simulation model supporting the design process has to be validated with further experiments to gain knowledge on how to engineer such a reversible plant.

NOMENCLATURE

COP	Coefficient of Performance
E	Energy
EnCN	Energie Campus Nürnberg
HP	Heat Pump
ORC	Organic Rankine Cycle
P&ID	Piping and Instrumentation Diagram
PLC	Programmable Logic Controller
POE	Poly-ol-ester
t	time

Subscript

el	electric
th	thermal

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ACKNOWLEDGEMENT

We would like to offer our special thanks to BITZER SE and SWEP International AB for the support with products and to the Bayerische Staatsregierung for financing the project within the Energie Campus Nürnberg (EnCN) [grant number IX.6-F2421.4.0/22/31].