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Lubrication management of a reversible compressor-expander-unit in a combined HP-ORC-plant

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Abstract

Combining a heat pump cycle with an Organic Rankine cycle and adding a thermal storage enables an innovative and reversible energy storage concept. As both processes use similar components, it is conceivable to combine these in one single cycle with two operation modes.
Within an ongoing research project at University Erlangen-Nuremberg, a combined HP-ORC pilot plant is designed and constructed. One focus in the research is the combination of the compressor of the heat pump and the expander of the ORC in one single machine (e.g. screw-type). Besides the pressure ratios and temperature levels, the lubrication is an interesting challenge, as it differs in quantity and function.
Several innovative designs of the lubrication system are conceivable. The oil separator is an essential component of the lubrication circuit. With methods of CFD-simulation, a close look at the separation in both operation modes (HP and ORC) is possible. This paper describes preliminary considerations, shows design methods and identifies solutions for the lubrication management of a reversible compressor-expander unit.

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Keywords: Combined HP-ORC; Carnot-Battery; Lubrication; Combined compressor-expander; CFD; Simulation

Nomenclature

HP	Heat Pump
ORC	Organic Rankine Cycle
CFD	Computational Fluid Dynamics
E	Energy
PV	Photovoltaics
Π	pressure ratio
p	pressure
θ	volume ratio
κ	isentropic exponent
C	compressor
E	expander
S	separator
VOF	Volume of Fluid
DPM	Discrete Phase Model
η	efficiency
n	number

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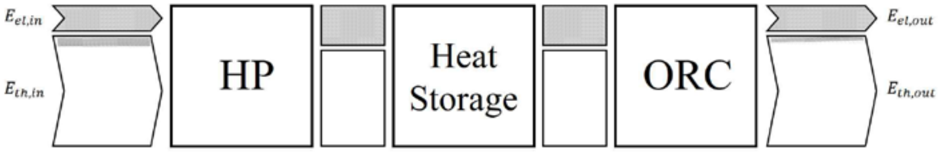


Fig. 1. Diagram of energy flows for the HP-ORC-concept (el.: electric, th.: thermal)

1. The combined HP-ORC-concept

1.1. Fluctuating renewable energies and the need for energy storages

Reaching the goals of the *Paris Agreement*, a significant increase in the electrical power production coming from renewable energy sources takes place. Due to the fluctuating character of renewables (especially PV, wind) improvements of energy distribution and storage are strongly required [1]. Several storage concepts are known, which differ greatly in storage capacity, efficiency and lifecycle-costs, so that there is a different area of application for each. *Pumped Thermal Energy Storage* is a big scale medium-term concept group that includes the *Carnot Battery,* a combination of heat pump and Organic Rankine Cycle.

1.2. The HP-ORC-concept (Carnot Battery)

The heat pump cycle (HP) is a well-known method to lift a medium's temperature by using electrical energy in a very efficient way. The Organic Rankine cycle (ORC) is a system that converts heat or thermal energy to mechanical energy and (via a generator) electrical energy. Using both concepts together and adding a thermal energy storage leads to the combined HP-ORC-concept (see figure 1). The concept also known as *Carnot Battery* can act as medium-term electrical energy storage. Electrical energy to be stored runs a heat pump cycle using waste heat energy to increase the temperature level of a thermal storage medium. In case of need, an Organic Rankine cycle converts the thermal energy of the storage medium (lowering the temperature level again) back into electrical energy. The achievable power-to-power efficiency and storage capacity strongly depends on the temperature levels of the application [2]. As both processes consist of similar components, it is possible to combine the cycles using the components reversibly and save investment costs.

2. Reversible use of a compressor and expander

The combination of a heat pump cycle and an Organic Rankine cycle requires some further considerations. The heat exchangers, being the most expensive parts of the cycles, can already reduce the investment costs significantly when used reversibly [3]. A diverse task is the combination of the compressor (HP) and the expander (ORC) in one single machine. The combination is conceivable for any type of volumetric machine [4]; in the current case, a screw type is investigated. Comparing the two operation modes of the concept, the outstanding differences are the temperature and pressure levels of condensing and evaporating and thus the inlet and outlet conditions of the machines. While the temperature variations are manageable, the different pressure levels are a relevant factor for process design. One fundamental number of the compression or expansion step is the pressure ratio Π, which is defined as the ratio of the higher pressure to the lower pressure:

$$\Pi_{compression} = \frac{p_{out}}{p_{in}} \quad (1)$$

$$\Pi_{expansion} = \frac{p_{in}}{p_{out}} \quad (2)$$

During the heat pump mode, the working fluid's temperature rises from the temperature level of the waste heat (where the evaporation takes place) to the upper storage temperature (where the condensation takes place). Applying the ORC, the working fluid reduces its temperature from the upper storage level (evaporation) nearly

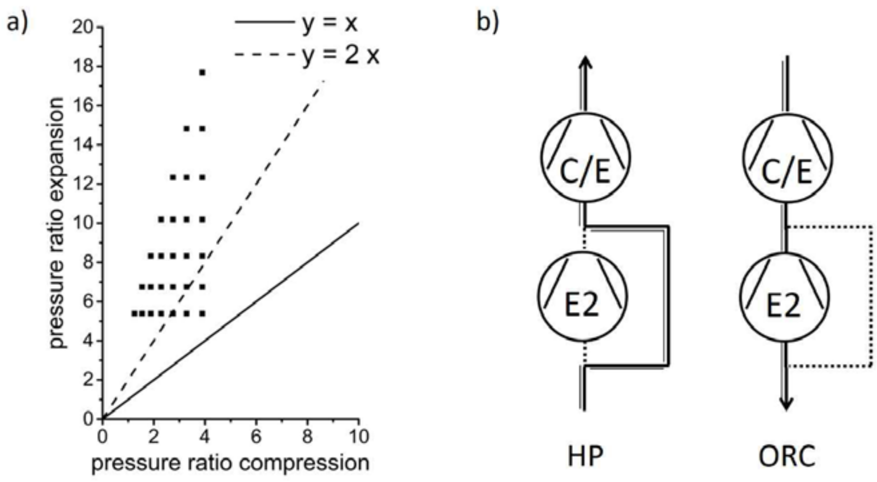


Fig. 2. Comparison of pressure ratio for compression and expansion (a) and concept of combined machine layout (b)

down to ambient temperature (condensation). Since the temperature levels of the phase changes differ in the two modes, the pressure ratios at the machines differ significantly, being much higher in the ORC-case. Figure 2a) shows these numbers for different temperature scenarios (dots) of the storage concept. The full line in the figure indicates the symmetrical case, when the pressure ratio at expansion equals the pressure ratio at compression. Regarding the location of the typical operation scenarios of a combined HP-ORC-application, apparently this case does not occur. The location of the operation field is much more in the range of

$$\Pi_{expansion} = n \cdot \Pi_{compression} \quad ; with\ n = 2; 3 \tag{3}$$

Particularly for volumetric machines (e.g. screw compressor, screw expander), there is a fluid sensible relation between the built-in volume ratio θ and the pressure ratio, with κ being the isentropic exponent [5]:

$$\Pi = \theta^{\kappa} \tag{4}$$

Equation (4) shows the challenge to select a single machine, which meets the requirements of both compression and expansion having different pressure ratios. A solution to this is a serial approach as seen in figure 2b). Adding an extra expansion unit (E2) to the reversible machine (C/E) in expansion case (ORC) and bypassing it in compression case (HP) enables two different pressure ratios. These can be adjusted to the main operating point by the selection of proper machinery.

3. Lubrication of a combined machine

The lubrication of screw machines brings several advantages (no need of gears, better sealing, temperature regulation) thus an oil-injected compressor or expander is frequently used. Still the lubrication comes with some challenges especially for a reversible use. It differs for compressors and expanders due to the reversion of the thermodynamic process. In the compressor, the main function of the lubricant is the heat transport: the cooling of the compressed gas is necessary to increase the efficiency and lower the thermal load on the component parts. In contrast, there is no cooling necessary for the expander case, because expansion of the gas already lowers its temperature. That leads to a difference in the mass flow of the lubricant, being smaller in the expander-case.

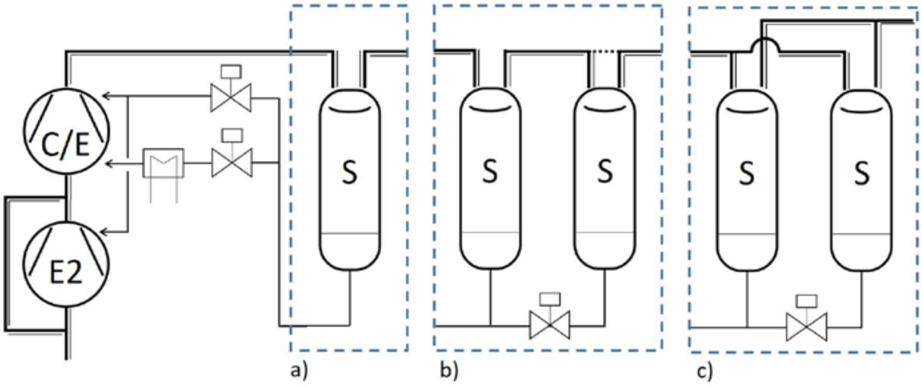


Fig. 3. Lubrication chart of combined compression-expansion-machine with: a) single separator, b) two serial separators, c) two parallel separators

One main part of the lubrication circuit is the oil separator, which divides the refrigerant vapour from the oil. Here again, two different approaches have to be compared: While in the HP-case, it is straightforward to locate the separator downstream of the compressor, cool the separated lubricant and re-inject it at the low-pressure side, the separation process for an expander is often quite different. Locating the separator downstream as well would lead to a huge apparatus because of the bigger volume flows at low pressure. To avoid this, it can be placed upstream. That leads to the fact, that the lubricant follows the refrigerant's way all through the ORC and is separated just before the expander, to be injected into the proper places. Due of the relatively low mass flow, the lubricant does not affect the refrigerant circuit too much. Furthermore, this setup enables the combination of the lubrication for a combined compressor-expander-unit very well (see figure 3a)).

Nevertheless, the different mass flows of lubricant and different volume flows of refrigerant influence the design of the separator particularly. Several layouts are conceivable: to adapt the performance to each case it might be necessary to add a second separator. It can be placed as a serial (figure 3b)) or parallel setup (figure 3c) improving the separation efficiency or halving the volume flow respectively. For further investigations of the fluid dynamics in a vapor-liquid-separator, numerical analysis was carried out.

4. Fluid dynamics in oil separators

4.1. CFD model

The main function of this setup is to enable vapor-liquid separation for the HP-mode and ORC-mode. Therefore, it is necessary to use a symmetrical separator design. In general, the vertical vapor-liquid separator consists of four sections [6]: the inlet diverter, the gravity settling section, the liquid collection section and the mist extractor. In this study, both the vapor-liquid inlet (diameter 0.03 m) and the vapor outlet (diameter 0.03 m) are placed on top of the vessel (diameter 0.12 m, height 0.4 m), which are separated by a divider to prevent short cut flow. Droplets of liquid settle in the liquid collection section, where an outlet for the liquid is placed at the bottom of the vessel.

To predict the fluid flow behavior inside the separator and to calculate the separation efficiency, Computational Fluid Dynamics (CFD) is used. There are two approaches for multiphase flow modeling: Euler-Euler and Euler-Lagrange. For the Euler-Euler method, continuous-continuous phase interactions form a discrete interphase between them. They are immiscible with each other and it focuses on the fluids motion in a specific location. With the Euler-Lagrange method, the fluid is considered as continuous phase, while the disperse phase can be solid particles liquid droplet or gaseous bubbles. Each particle is tracked separately and the motion can be predicted.

Studies of vertical gas-liquid separators [7,8] have shown a combination of the volume of fluid (VOF) model, as a simplified version of the full Eulerian model, with the discrete phase model (DPM) is suitable for simulation of multiphase separation processes. Hereby oil-droplets as a dispersed phase are solved under a

Lagrangian frame until it reaches the final destination where boundary conditions apply and the vapor as continuous phase is solved using an Eulerian frame of reference.

4.2. Boundary conditions

In this study, a steady vapor-liquid simulation is implemented in ANSYS FLUENT 19.1. With the criteria of quality and skewness of the mesh, a computational mesh-grid-independent solution was performed. Prism layers were set at the wall and tetrahedral elements placed inside the separator. To save computational time, a symmetric boundary condition was placed. The Reynold Stress Model (RSM) calculates turbulence. The inlet mass flow was defined accordingly to table 1 for the liquid and vapor phase for the following simulated cases. As it typically appears for the storage concept, the mass flow in the ORC-case is slightly smaller than in the HP-case. The droplet size of the oil in the vapor stream follows a particle size distribution. As there is no physical data for the specific case available, the mean droplet size is assumed to be 250 microns. This will be valuated experimentally in a pilot plant set up. For the serial HP-mode, just the second apparatus was simulated, as the first one is identical to the single HP-mode. The inlet conditions at the second separator are equal to the outlet conditions of the first; the droplet size is reduced to 150 microns, assuming the smaller particles to be less separated in stage one. In the parallel HP-mode, vapor and oil mass flow is halved. Static pressure was set at the outlets as for the bottom outlet hydrostatic pressure was set. Furthermore, phase interaction, Ishii Zuber drag forces and virtual mass are included. The surrounding fluid flow remains unaffected by the droplet motion. Physical transport processes, which take place at the phase boundary surface (warm and cold transport), are not considered in this work.

Table 1: Fluid properties for HP- and ORC-modes

	HP- mode, single	ORC-mode, single	HP- mode, serial (2)	HP- mode, parallel (1/2)
Gas flow rate	0.3 kg s^{-1}	0.2 kg s^{-1}	0.3 kg s^{-1}	0.15 kg s^{-1}
Liquid flow rate	0.04 kg s^{-1}	0.02 kg s^{-1}	0.004 kg s^{-1}	0.02 kg s^{-1}
Operating pressure	163800 Pa	91300 Pa	163800 Pa	163800 Pa
Operating temperature	411 K	368 K	411 K	411 K
Gas density	83.61 kg m^{-3}	48.78 kg m^{-3}	83.61 kg m^{-3}	83.61 kg m^{-3}
Liquid density	1048.48 kg m^{-3}	1048.48 kg m^{-3}	1048.48 kg m^{-3}	1048.48 kg m^{-3}
Droplet size	250 µm	250 µm	150 µm	250 µm

4.3. Simulation results and discussion

Stochastic model of turbulent dispersion is included in the particle trajectory calculations. 10500 particles were injected at the inlet. Through the DPM, escape zones and trapped areas were assigned to count the particles, which reached the liquid collection section. Equation 5 provides the predicted separation efficiency with the number of oil droplets at inlet and outlet:

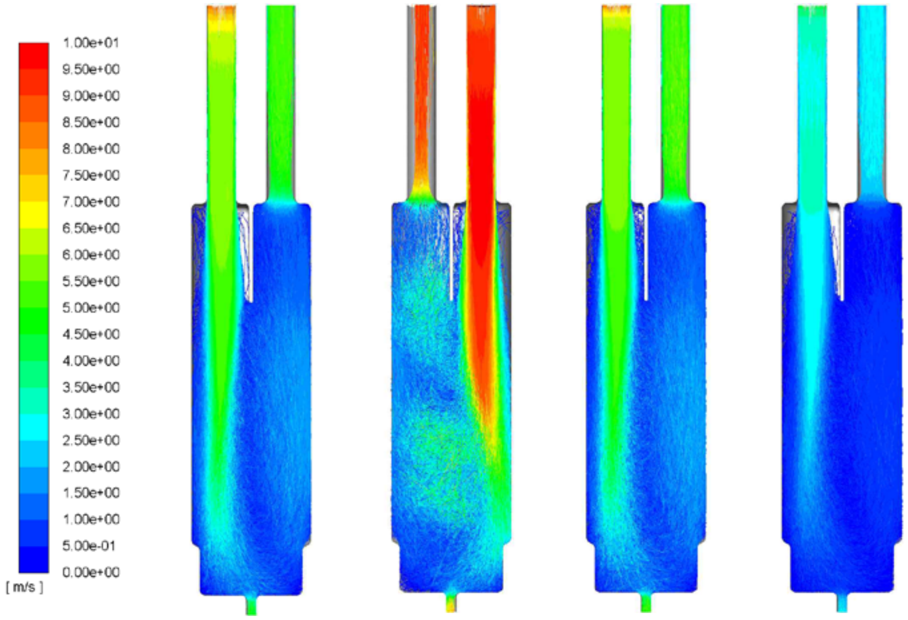
$$\eta = \left(\frac{n_{oil,in} - n_{oil,out}}{n_{oil,in}}\right) \cdot 100\ \% \tag{5}$$

Table 2 shows the calculated separation efficiencies for the considered cases.

Table 2: Separation efficiency

Case	HP-mode, single	ORC-mode, single	HP-mode, serial (2)	HP-mode, parallel (1,2)
Separation Efficiency	89.4 %	98.6 %	86.9 %	84.3 %

Figure 4 shows the particle velocity magnitude for the four different cases. The inlet is on the left for HP and on the right for ORC. According to the simulation results, separation in HP-case could reach an efficiency of about 89 %. An improvement because of parallel use of two similar separators cannot be seen, even though the volume flow halves (84 %). Conversely, a second serial apparatus can increase the separation efficiency furthermore (89 % at first stage, 86 % at second stage) reaching in total a number of 98.6 %. Having a symmetrical geometry, the reversible use of the separator in the ORC-case is not an issue per se. Yet the inlet conditions change (lower pressure and therefor lower density), resulting in different flow conditions. Here a separation efficiency of about 98 % results. Further simulation results show a strong dependence of the particle size.



particle velocity magnitude | a) HP-mode, single | b) ORC-mode, single, reverse inlet | c) HP-mode, serial (2) | d) HP-mode, parallel (1/2)

Fig. 4. Particle velocity magnitude of oil droplets in different separation setups

To sum up, the separation efficiency is mainly a function of particle size, volume flow and lubricant mass flow. Combining a heat pump compressor and an Organic Rankine cycle expander two different lubrication situations meet. Of course, it is feasible to find an optimal separator for each task, but combining the function in just one separator comes with smaller declines. The study shows that separation in ORC-mode is slightly more efficient; hence, the separation apparatus should be bigger in HP-mode. This challenge can be resolved by adding a second apparatus. Here the study shows an advantage of the serial setup compared to the parallel one. Even though the results are valid in general, the droplet size assumption has to be confirmed experimentally and updated to the simulation. Therefore, a pilot plant setup of the combined HP-ORC concept will be launched in 2020.

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