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High temperature test results and application cases of a Rotation Heat Pump

Andreas Längauer[a*], Bernhard Adler[a]

[a]ecop Technologies GmbH, Perfektastraße 73/Top A1, 1230 Vienna, Austria

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Abstract

The environmentally friendly working fluid, based on noble gases like Helium, Argon and Krypton, is used in the counterclockwise Joule-cycle in a Rotation Heat Pump (RHP). Combined with centrifugal compression this leads to a very high Coefficient of Performance (COP) at high sink outlet temperatures compared to conventional compression heat pumps. Since the realized Joule-Cycle is based on an always gaseous working fluid, the heat transfer in the heat exchangers is sensible. Therefore, neither the issue of lubrication of the compressor nor the critical point of the working fluid limit the maximum sink output temperature. The data shown provides information about the electricity consumption, the flow temperatures and the heat output provided by the system. The results show that the prototype of the RHP K7 can achieve a COP >3.5 for sink outlet temperatures *higher* than *100 °C*. The correlations between the main rotor speed, temperature spread and thermal power are analyzed for the test run as well. Based on this, application cases in the industry and the field of energy services are presented and the advantages of the Rotation Heat Pump are described. Those are, for example, the high spread of sink and source when providing cooling and heating as well as the flexibility using one machine at different temperature levels. Further, an outlook for adaptions to realize sink outlet temperatures >150°C will be given.

Keywords: Rotation Heat Pump, Test Results, High Temperature, Application Cases

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Introduction

An enormous amount of energy is required in industry in the form of heat, De Boer et al [1]. In many cases, the temperature level is between 100 °C and 200 °C, Fleiter et al. [2], whereby the availability of heat pumps is limited, especially above 100 °C utilisation temperature. For this reason, many research projects and developments are being carried out with the aim of tapping this potential. Heat pumps are one of the key technologies in industrial applications and make a very large contribution to the reduction of CO2 emissions. By integrating them into different processes such as brick, food and feed drying, pasteurisation, distillation as well as chemical processes, the consumption of fossil fuels can be greatly reduced. The variety of applications, Schlosser et al [3], requires maximum flexibility of heat pumps as well as different technologies that can be used. The great potential of high temperature heat pumps in general and different implementation possibilities were described in Arpagaus et al [4], [5] and [6] as well as the currently still existing market barriers. Furthermore, the use of heat pumps in Austrian district heating networks is presented with examples in Arnitz [7] and the status quo and potentials of industrial heat pumps in Wilk et al [7]. Applications and potentials for industrial heat pumps in Switzerland are presented in Arpagaus et al [8]. Results of a propane-butane heat

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[*] Corresponding author. Tel.: +43 -1-865-10-62-27
E-mail address: andreas.laengauer@ecop.at

pump for high temperature applications are shown in Bantle [9]. Further synthetic refrigerants with low global warming potential and heat pump cycles are analysed in [10].

Due to the design of conventional compression heat pumps (CHP) with the main components - compressor, condenser, evaporator and expansion valve - heat is in most cases transferred latently (i.e. by evaporation or condensation of a refrigerant). This means that comparatively high mass flows of the process media are necessary to scale up the performance if small temperature spreads between source inlet and outlet are to be achieved. Smaller spreads in conventional CHP are therefore to be aimed for, as this also keeps the temperature lift between condensation and evaporation low. The electrical power consumption of the compressor is reduced. The required compressor power has a direct effect on the COP (Coefficient of Performance).

The special characteristics and the design of the Rotation Heat Pump (RHP) make it possible to use heat pumps in new areas of application (hot air, steam, water) that have not been exploited so far.

Providing heat pumps for higher temperatures is very important and there has a lot of research been done in this area by different manufactures. Most of standard compressors in CHP are limited in terms of temperature by the working fluids and the lubrication. The RHP, using the Joule-cycle, is not limited by those factors for a temperature range >100°C. Based on previous publications, where the basic function, design, calculation methods and first test results of a Rotation Heat Pump have been published (Längauer et al., [11]), further tests are finished. Those are focused on higher temperatures at sink and source as well as showing how different parameters effect the Joule-Cycle in the RHP. Therefore, beside steady state conditions for sink and source also the start-up period and the shutdown process are explained. The test setup in terms of a scheme is described as well, which is essential to allow a comprehensible analyse of the test results. The aim is not to give a detailed calculation about COP including error estimations and tolerances but more to give an overview of the test procedure and how a certain measuring period looks like. Of course, detailed analyses are essential for accurate results when the COP is focused on. In this case tolerances of sensors are given but further calculations will not be implemented in this paper to keep the focus on temperature curves. The first part of the paper will give a short overview of the technology and references and further deal with this high temperature test of a RHP. After the results and discussion an outlook will be given for further tests. Also, the possibility to reach higher temperatures will be addressed and necessary changes will be given.

The Joule process implemented in the RHP realises a wide spread of both heat source and heat sink due to the sensitive heat transfer and is especially optimally suited for this purpose. In contrast to CHP, the temperature lift and the compressor capacity are decoupled from the spread. They can be controlled almost independently of each other. The COP therefore remains at a high level compared to the CHP, with a similar temperature range and a spread of up to 30 K. The strong cooling of the source offers the advantage of transferring very large heat outputs from the process water to the working fluid at lower mass flows. This means that not only the pipelines, but also other peripherals such as pumps, filters, etc. can be dimensioned much smaller. The high efficiency of RHP with large spreads brings great advantages in terms of costs and application in industrial processes with specified cooling or target temperatures (provision of cooling water).

The efficiency of heat pumps is usually compared using the COP at certain operating points. Together with other criteria, this is ultimately decisive for the final selection. As boundary conditions, often only the temperature at the inlet of the source and the temperature to be aimed for at the outlet of the sink are mentioned here. In combination with the thermal power and the mass flow, the other temperature levels are finally determined based on thermodynamics. If a fluid with a very high heat capacity flow is available as the source, it is of little or no relevance if the thermal power is primarily achieved via the mass flow. This could be the case, for example, when using river water, geothermal energy or similar heat sources. In many industrial processes, however, these mass flows are limited and thus thermal power must be seen as a product in which the temperature difference factor is much more important. This plays a major role in the dimensioning of heat pumps. It is therefore essential to consider the temperature spread of source and sink when designing and considering implementation options. Examples of this are various heating processes such as the provision of hot air, hot water or steam or air preheating for drying processes (e.g.: Wilk et al. [12]). A second part of this paper will discuss and show how the thermodynamic process is affected by having high spreads for sink and source in a CHP and RHP. For this purpose, a conventional HFO (Hydrofluoroolefine) refrigerant - R1336mzz(Z) with low GWP (Global Warming Potential) and the Joule process as implemented in the RHP with a noble gas mixture as working fluid are compared in an industrial process for distillation. Also, some more application cases will be shown and discussed where the temperature spread is essential and an advantage.

1. Main Principle

In the RHP, the counterclockwise Joule cycle is realised whereby the working medium used is always gaseous. The compression is realised by centrifugal forces, the pressure and the temperature increase outwards due to the rotation (approximately adiabatic compression). This principle was first presented in Adler [13] and further in Adler [14], [15]. Further descriptions, explanations and test results can be found in Adler and Mauthner [16], Längauer [11], [17]. Since the technology is worldwide patented and there is no other manufacturer providing it, only references by ecop can be given. Essential for the function is the centrifugal acceleration occurring due to the rotation, which causes the compression of the working gas. Thus, a very efficient compression can be realised, since the relative velocity of the working gas in the pipes is very small compared to the absolute velocities. Figure 1 schematically shows the Joule process in an RHP**.**

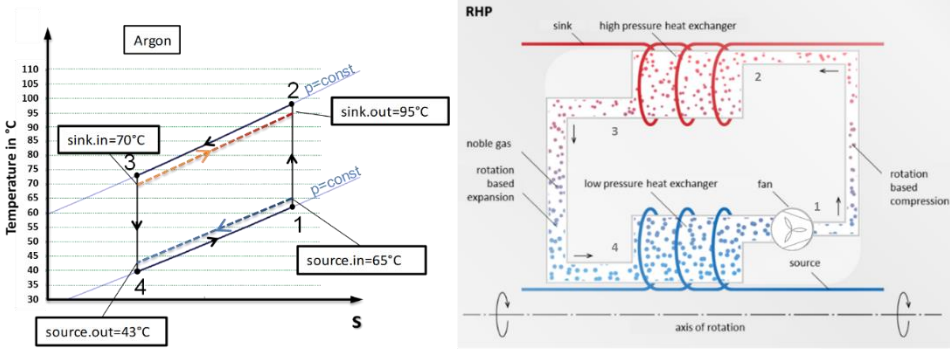

Figure 1: Schematic representation of the cycle process in an RHP [17]

2. High temperature test

2.1. Test setup

To test the performance of a RHP a test rig is used which is connected to the sink and source of the RHP. The two different circuits are each closed and mass flow is ensured by pumps. Temperatures are measured at the RHP as well as at the test rig where also the mass flow is captured. The electrical power consumption is measured via frequency converters which are used for controlling the rotational speed of the components as well. All sensors and components necessary are connected by a Bus-system with the programmable logic controller where the signals are postprocessed and the final value is stored in a file. Beside several sensors and pumps the test rig also includes heat exchangers which are used to recover heat during the test process. Much less energy than the thermal output at the sink has to be dissipated to the environment because of this arrangement. For steady state conditions the electrical power consumption of the fan and rotor, which are finally transformed to heat, have to be dissipated. Therefore, a separate circuit including two water-air heat exchangers with fans (Fan1, Fan2), is used. The following Figure 2 shows the RHP-K7 and the test rig during the test process.

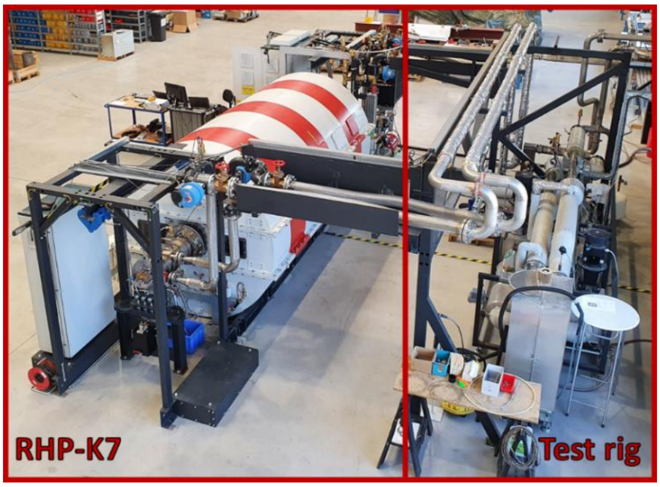

Figure 2: RHP-K7 and Test rig at production site

Essential components and sensors as wells as details about the measurement system and configuration are given in [11]. They will not be summed up here again. Also, the COP calculation is based on this publication, it should only be mentioned here, that for the COP the thermal power at the sink side and the electrical power consumption of the main rotor plus the fan engine are used.

2.2. Results and discussion

In the following section test results based on the test setup described above will be shown and discussed. Therefore, one day of testing is split in three sections which will each be illustrated in a quartet of diagrams. They will include measured values of temperatures (sink and source), electrical power consumption, mass flows, thermal power (sink and source) and COP. This is useful to explain the behaviour of the RHP for different conditions and the corresponding results. The first section will describe the ramp up of the Rotation Heat Pump, the second section will discuss the curves for almost steady state and the third section will be about the shutdown of the System. To give an overview, the following diagram (Figure 3) of the temperature curves shows the related sections. The shown test was started at 07:00h and lasted till 17:30h. After the results are presented, a short discussion will follow where different effects of changed boundary conditions are analysed.

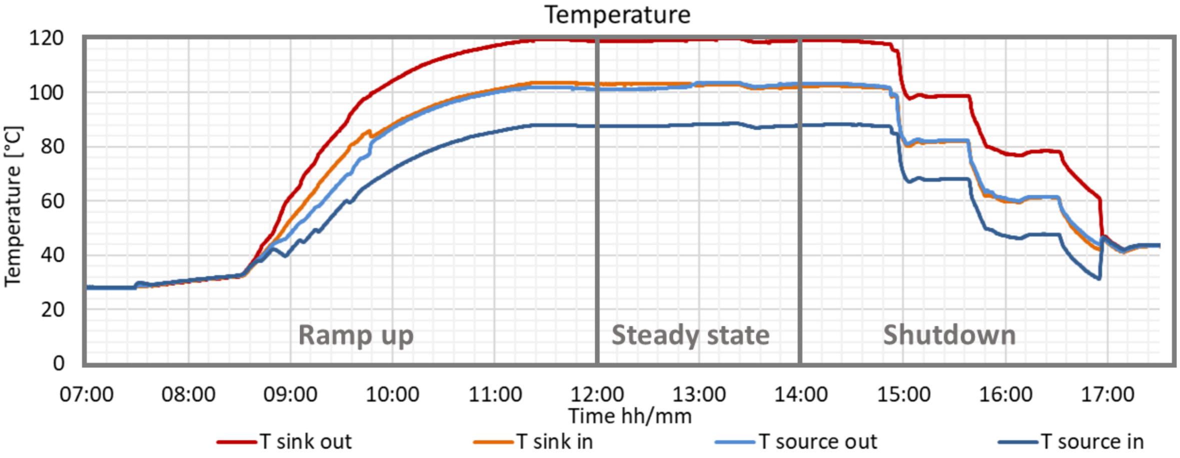

Figure 3: Temperature curves of sink and source of testing day including different time periods

The ramp up time represents the time where the system is started and heated up from initial conditions. Figure 4 shows the mentioned curves for these conditions. Initial conditions means that there is no rotation whether of the main rotor or the fan and there is no mass flow of working fluid or process fluid. The temperature level of sink and source are almost equal at the inlet as well as at the output. The test run starts by ensuring mass flow of sink and source just after 07:30h (Figure 4b) while at around 8:30h the fan, which provides the mass flow of the working fluid, is switched on. This can be seen by the electric power of the fan in Figure 4c. It is essential, that the mass flow of the working fluid is already built up before transferring thermal power at sink and source because otherwise the pressure increase necessary for the process can't be ensured by the fan. Last step is to start up the main rotation which generates the temperature lift between sink and source, Figure 4b. This can be seen just a few minutes after 08:30h, the mass flow of the working fluid is already ensured. The COP at this time is not representative because there is still a certain amount of heat necessary to heat up the whole machine. As can be seen in Figure 4a, the temperature of sink and source generally increases over time while the temperature difference between sink outlet and source inlet increases as well. General increase is caused by heating up the system by internal electrical components and an external heater mounted on the pipe system at the test rig. The temperature difference, means the temperature lift between sink and source, increases because of the increasing rotational speed of the rotor.

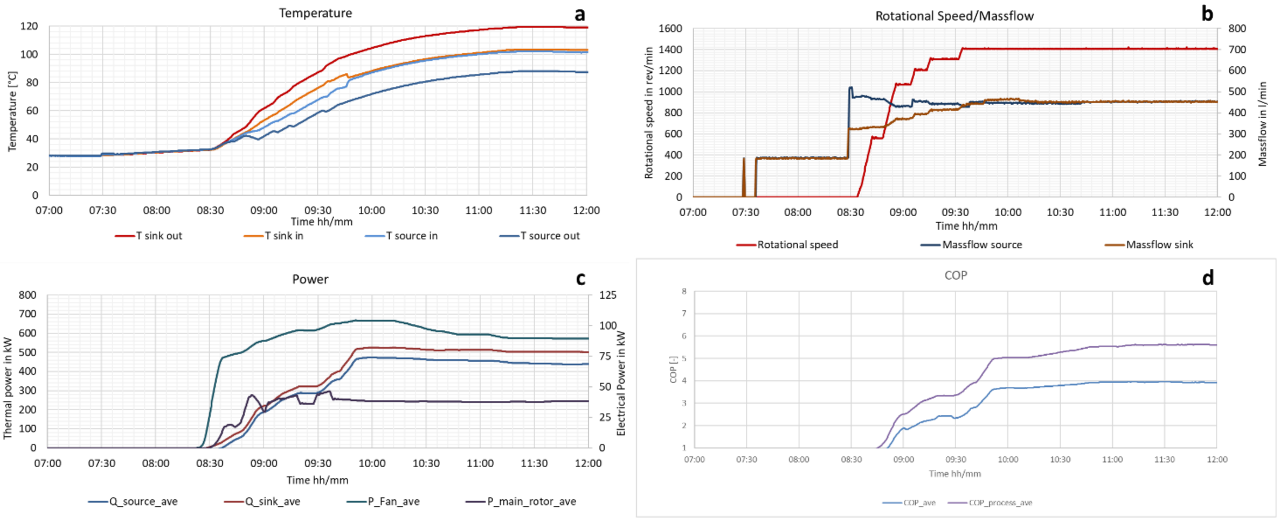

Figure 4: Ramp up – Temperature (a), rotational speed and mass flow (b), thermal and electrical power (c) and COP (d)

The second time section displays the performance of the RHP at almost constant boundary conditions, shown in Figure 5. After the ramp up the temperatures for sink and source at the inlet are kept constant. Also, mass flow and rotational speed of the main rotor are set to a certain level. For this test 1400rpm are defined for the main rotor and approximately 460l/min are the flow rate of sink and source. Since the test rig is a circuit of limited volume, the controller is not finally optimised yet and as much heat as possible is tried to be recovered, some small drifts of temperature and thermal power occur. Nevertheless, the temperature at sink outlet is kept at around 120°C, which demonstrates the possibility of providing high temperatures while the COP results in around 4 and COP_process is around 5,7-6. The thermal power at the outlet is 500-550kW. A small deviation of thermal power and COP can be seen a few minutes before 13:00h, where the rotational speed of the fan engine was increased slightly and the inlet temperatures have been adjusted.

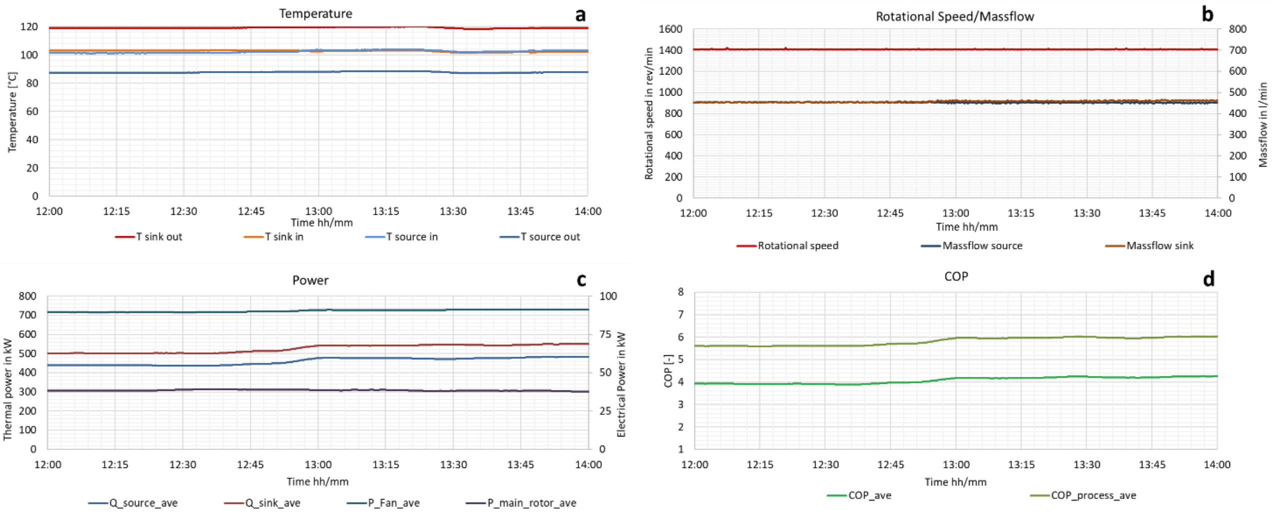

Figure 5: Steady state – Temperature (a), rotational speed and mass flow (b), thermal and electrical power (c) and COP (d)

The last section, Figure 6, describes variations and the shutdown of the system which means that it shows how the temperature is lowered and finally the rotational speed of the rotor decreases until it stops. Also, at the beginning variations of the rotational speed of the fan and how they affect the Joule-cycle and the system are shown. Starting at 14:00h, the temperatures correspond to the level of the steady state shown earlier. A few minutes after 14:00h the rotational speed of the fan is reduced which can be seen by the decreased power consumption of the fan-engine. Because of fluid mechanics, lowering the fan speed goes along with reducing mass flow and pressure increase. This results in lower flow velocities and less flow losses but also less heat transfer in the heat exchangers. Consequently, the transferred heat also decreases, as can be seen in Figure 6c. As a result, however, the COP increases because the ratio of thermal power and electrical power consumption increases. In particular, the COP_process increases since the fan works more efficient. After lowering the rotational speed of the fan, the first temperature step downwards takes place at around 15:00h. At this time more heat is dissipated via the external heat exchangers of Fan1 and Fan2. Sink outlet temperature decreases from 120°C to 100°C and also inlet and outlet temperatures of sink and source are dropping around 20K. Since this is a dynamic process the thermal power and the COP calculation are showing values for unsteady conditions. The heat capacity of the rotor and the whole system would have to be included at this point because the temperature level of all components is decreased. After this drop the system is in a steady state condition after a few minutes again. About half an hour later the next temperature drop takes place and the system temperature is lowered again 20K. Heat output and COP show the same characteristics as before and after a few minutes steady state operation is reached again. Looking at the COP in general, it almost does not depend on the temperature in steady state. In the next steps the temperature is further lowered and just a few minutes before 17:00h the fan is switches off and there is no more thermal power delivered, all temperatures equalise and finally the values for COP are not representative anymore. Before the last step, where the pumps for the process fluids are switched off, the engine for the main rotor is switched off and the rotational speed is reduced. The peak of the main rotor power consumption at 17:00h can be explained as follows. For a final shutdown when the rotor has to stop, valves in the housing are opened to allow ambient air to flow into. Basically, till all tests a vacuum is provided inside the housing to reduce ventilation losses of the rotor. In this case, just before the engine is switched off, the valves are opened, air flows into the housing and so the power consumption of the main rotor is for a short time higher than usual.

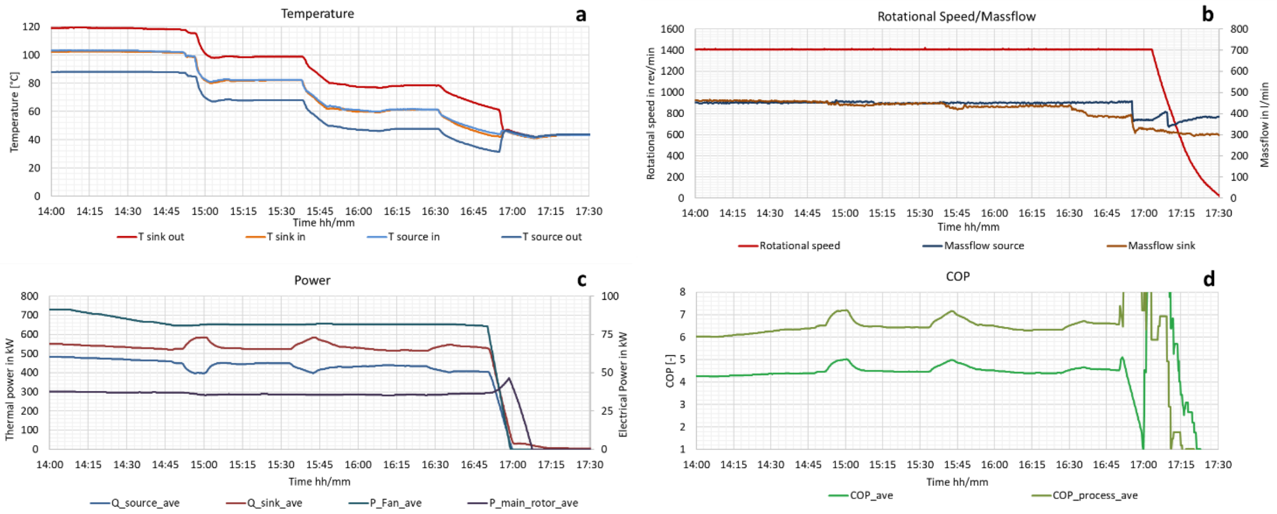

Figure 6: Shutdown – Temperature (a), rotational speed and mass flow (b), thermal and electrical power (c) and COP (d)

3. Application Cases

3.1. Distillation

For the calculation of the thermodynamic processes, the same values for the CHP and RHP were assumed regarding the temperatures of the source and sink, the mass flow and the thermal power. The results are based on [18], where more detailed analyses are given. The spread given in the calculations is assumed to be the same for both source and sink. Since the refrigerant R1336mzz(Z) has a strongly overhanging wet vapor region (see also Helminger [19]), superheating after the evaporator is also applied in the calculation. Furthermore, in the CHP process, no peripheral losses such as the power of the control system or auxiliary devices that influence the process or COP are included. Application - Distillation process

In addition to the results presented so far with specified boundary conditions, as can occur in industrial processes, the two heat pump processes are compared below for the specific application case of a distillation process in whisky production. In this application, the ethanol-water mixture is evaporated in the still (distillation column). This takes place at 85 °C to 95 °C and is usually realised with saturated low-pressure steam. In this application, an inlet temperature of 120 °C and an outlet temperature of 90 °C are required. In principle, the distillation process (latent heat) is also possible at constant temperature. This process can also be implemented with process water, but the spread must be correspondingly large (30 K). At the same time, the heat of condensation and cooling that must be dissipated in the downstream condenser can be used as a source. This application thus has the advantage that both the cooling of the source and the heating of the sink can be used. Figure 7 shows the integration schematically. The boundary conditions are the

- Temperature at the inlet of the source with 85 °C,
- Temperature at the outlet of the source with 55 °C,
- Temperature at the inlet of the sink with 90 °C,

Temperature at the outlet of the sink with 120 °C

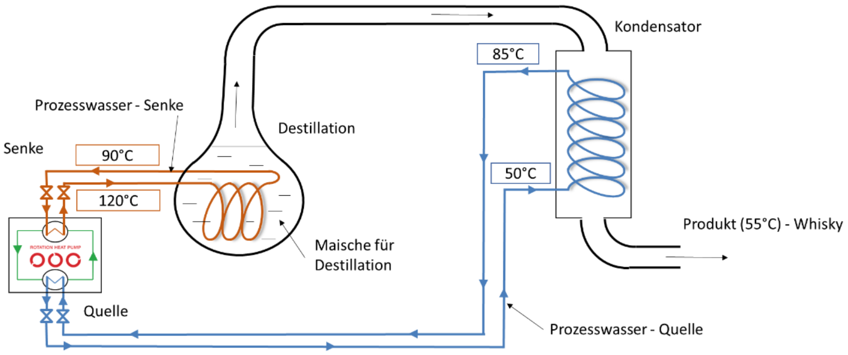

Figure 7: Continuous distillation process of ethanol in combination with an RHP

The spread is 30 K, whereby the lift for the evaluation according to source inlet to sink outlet temperature is 35 K and 65 K for source outlet to sink outlet temperature. The thermal power is also given in this case with 700 kW and is assumed to be the same in both designs. Figure 8 below show the thermodynamic cycle for the RHP and CHP for the given boundary conditions where a COP of 4,7 for the RHP and for the CHP a COP of 3,7 can be calculated.

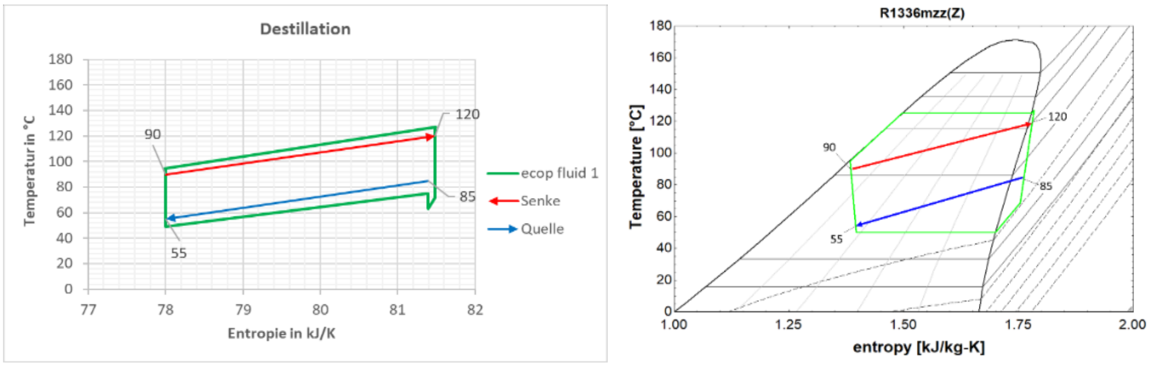

Figure 8: Calculated cycle for application in distillation (source inlet/outlet: 85 °C/55 °C, sink inlet/outlet 90 °C/120 °C), (left: Joule process of RHP, right: 2-phase process of CHP)

3.2. Cooling

Many industries need to dissipate enormous amounts of heat for the cooling of engines/generators/processes, this heat can often not be used directly due to a relatively low temperature level. With the Rotation Heat Pump, it is possible to both provide the cooling with high temperature spreads, this energy is used as a source, and to provide heat again at a high temperature level. E.g., for self-consumption for heating support or for feeding into a district heating network. Heat and cold can thus be provided with one system.

3.3. Pasteurization

In the pasteurization process, products must be heated in the first step and then cooled again. Until now, these processes have often been considered separately. However, it is much more energy-efficient to use the heat available during cooling and to use it for heating at the beginning by means of a temperature lift in a Rotation Heat Pump.

3.4. Hydrogen production

In hydrogen production, water is separated into Hydrogen (H_2) and Oxygen (O_2) by an electrolysis process. The water provided must be cooled and fed back into the process. To make hydrogen production as efficient as possible, it makes sense to use this heat for other processes. Depending on the operating temperature of the production process, many electrolyzers use temperature levels of around 40-70°C which is to less for direct using most of the time. Combined with a Rotation Heat Pump, a large spread at the source can be achieved to cool the water and then feed the heat into e.g., a district heating network or a production process at higher temperature levels.

3.5. Steam generation

Steam can be obtained directly from the hot water by pressure reduction in a steam drum. This eliminates the need for an additional heat exchanger and allows the full temperature level to be utilised, as steam is fed directly into the system via a steam lance. Pressure control units allow precise control of the steam pressure as well as the hot water to prevent evaporation in the heat pump. The amount of used steam is fed back into the system in form of feed water via a feed water tank.

4. Results and discussion

The presented results of a high temperature test run show that due to the flexibility of the Joule-cycle the temperature level is not essential to operate a RHP efficiently. During the ramp up time it is necessary that mass flow of the working fluid is already ensured before the main rotor speed is increased. Otherwise, it is not possible to overcome the pressure difference caused by the thermal power transferred at the heat exchangers. This pressure increase is mainly depending on the thermal power and the temperature lift. Temperature lift is mainly produced by the rotational speed of the main rotor. By adjusting the rotational speed of the rotor, the temperature lift can be controlled as well as the thermal power for given conditions can be adjusted. Of course, different control strategies can be obtained for this system by having those parameters to control. This is already in progress and will be tested as soon as possible in a first step on digital twins and finally at the test rig combined with the RHP. Having different control strategies also tests will be adapted and can be much more dynamical. Changes in temperature, mass flow, rotational speed and other parameters can then be made easily under exact control. This will allow a much more detailed analyse of the system under dynamic boundary conditions. Probably the sampling rate of the logging must be adjusted to get finer results since now it is set to 5 seconds. In addition, accuracy of sensors should be considered and analyzed in a next step.

Table 1 shows the COP for the given operating points before. They are based on theoretical calculations with 700 kW thermal power at the sink. Most of the values of conventional heat pumps used for the specification of the temperature spread usually refer to the inlet temperature of the source and the outlet temperature of the sink. This approach is referred to as case 1 in the results. Another possibility is to calculate the temperature spread from the outlet temperature of the source and the outlet temperature of the sink. Case 2 describes this value.

Table 1: Overview of the operating points and calculation results

	Temperature of source in °C		Temperature of sink in °C		Temperaturelift in K			
Spread in K	Inlet	Outlet	Inlet	Outlet	Case 1	Case 2	CHP-COP	RHP-COP
30	100	70	120	150	50	80	2,91	3,87
30	85	55	90	120	35	65	3,72	4,68

The results show that the COP has a strong dependence on the temperature lift or on the temperatures used for calculating the temperature lift (source inlet/source outlet).

At a spread of 30 K, the difference between the two technologies becomes clear, with the RHP achieving much higher COP values than the CHP. This is possible due to the sensitive heat transfer as it occurs in the Joule process in the RHP.

Table 1 shows that the RHP achieves comparatively higher COP values as the temperature level rises. The reason for this is the Joule process implemented in the RHP, which enables very efficient compression due to the always gaseous working fluid at different temperature levels. The 2-phase process in the CHP is limited in terms of the maximum temperature level by the refrigerant. The COP decreases in the subcritical cycle in the CHP close to the critical temperature [6]. This effect does not occur in the RHP, since the working fluid permanently runs through the cycle in a supercritical state. Specifically for distillation, the RHP has a COP of 4.68 and the CHP a COP of 3.72. This can be explained by the high spread in combination with the high temperature level (120 °C sink outlet, 90 °C sink inlet, 85 °C source inlet, 55 °C source outlet).

Beside the specific shown case for a distillation process different application cases are shown were the high temperature spread provides a significant advantage for the process. Those applications provide for example cooling of a specific system or a high temperature difference at the process fluids is beneficial. A very interesting topic for high temperature heat pumps is also steam production which can be realized by using a steam drum. As a next step the combination and testing of a Rotation Heat Pump with a steam production system will be the aim.

4.1. Outlook for very high temperatures

The demand on thermal power at temperatures higher than 150°C up to 250°C in the industry is enormous. While right now temperatures of 150°C are possible by using a Rotation Heat Pump, it is already the aim to provide also these temperature-levels. Therefore, a completely new design of the rotor is developed which uses new technologies of manufacturing. The new method is based on a diffusion bonded system which includes heat exchangers and also the pipe system for water and the working fluid (only one solid block). A massive simplification is possible because all sealings at the rotor can be removed and so this method allows simple mass production. While also the size is reduced by more than 50% the efficiency can be increased by around 30% (due to smaller delta T in heat exchanger and reduced pressure drop). Following Figure 9 shows the difference in size and grade of simplification for a rotor providing same thermal power and temperatures. This new design will allow temperatures of up to 250°C and will be included in a prototype till 2024.

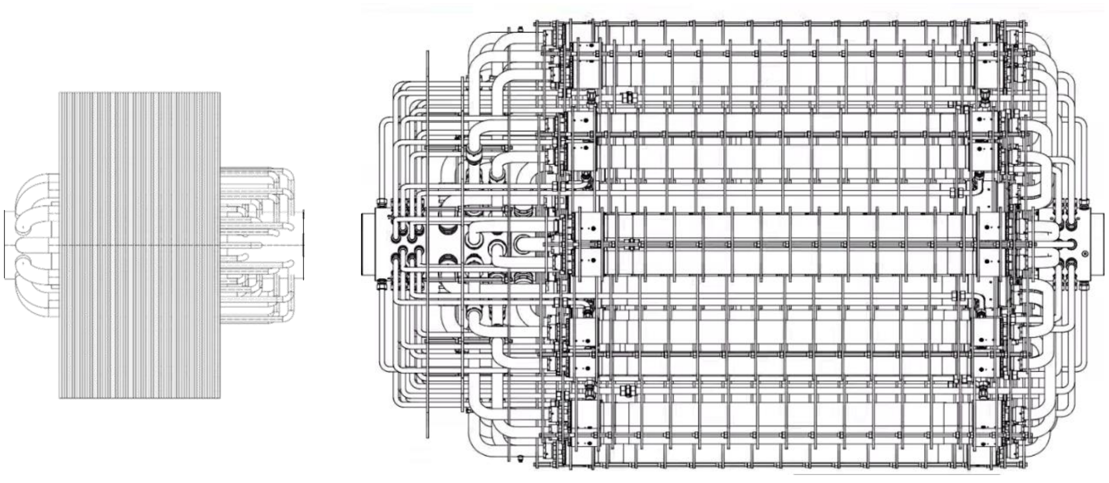

Figure 9: Comparison of rotor designs (same scale for both); Left: Integrated-Rotor design based on diffusion bonding, Right: assembled rotor-design

5. Conclusions

High temperature heat pumps play an important role to decrease CO_2 emissions since there are a lot of industrial applications using fossil fuels for heat supply now. The possibility to use the Joule cycle in a RHP allows using flexible temperatures and in addition the temperature level is not limited by the working fluid. To demonstrate the performance of a RHP at high temperatures, up to 120°C, a specific test run was set up and analyzed. Those test results were generated using a RHP-K7 in combination with a special test rig described in previous papers. The test data show an entire test day were also the startup period and shutdown time is included and analyzed. During the startup it is clearly shown how the temperature increases with time due to the heating up of the circuits. This takes some time but is not limited by the RHP but more by the electrical heaters. The RHP could deal with faster changes in temperature which is demonstrated during the shutdown. Also, the effect of increasing the rotational speed of the rotor can be seen and how this influences the process. This is a dynamic process where no steady state conditions are present and the evaluated COP is not correct by using classic formulations. Because the machine and periphery are heated up and can be seen as a thermal storage, energy balances are not fulfilled during this time. After the components have reached steady temperature levels the second time period of testing starts. This mainly includes steady state analyses where the parameters should not be changed. During this period measured sensor values and COP are almost constant without discontinuities. After having this constant test period, the third part describes the shutdown of the machine when the temperature level is reduced in a few steps. This shows that the temperature level can be changed within some minutes. Also, the thermal power can be adjusted in a certain range by increasing or reducing the speed of the fan. If the fan is finally turned off, no more mass flow occurs, and the temperatures all drop to an equal level. This test at 120°C could also be achieved for 150°C at sink outlet, essential is the use of adequate seals for this case to prevent leakage. Since the working fluid is not limiting the Joule-process itself, higher temperatures are feasible but of course some components must be updated.

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