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The Joule cycle realised in a Rotation Heat Pump

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ABSTRACT

The mainly used thermodynamic cycle realised in heat pumps is the so-called Plank cycle, at the theoretical maximum efficiency point ending up in the Carnot cycle. In contrast to this, a Rotation Heat Pump (RHP) is based on the Joule cycle where the compression of the environmentally friendly working fluid (no global warming potential) is accomplished by centrifugal forces. This results in a compression efficiency of more than 99%. Since there is no phase change during the heat exchange and the mixture of noble gases is always gaseous it is not depending on a certain temperature level.

The fundamental calculations and basics of the Joule cycle realised in a RHP including the derivation from the principle thermodynamics are presented in combination with different operating points and temperature levels. Further, analytical calculations are compared with complex 3D-simulations and also test results of a reference machine to demonstrate the function and performance.

Keywords: Rotation Heat Pump, Inert Gas, Joule Cycle, High Temperature, Flexible, COP.

1. INTRODUCTION

A Rotation Heat Pump, based on the counter-clockwise Joule cycle differs in many ways to a conventional heat pump based on the Plank cycle. A major point is the way how the compression takes place. While mostly piston, screw or turbo compressors are used, in a RHP centrifugal forces realise the compression and further the increase of temperature. This process is analysed in the following sections by first showing the basic principle and further, calculation methods for evaluating the thermodynamic cycle are introduced. The fundamental derivation of the centrifugal potential in context to the Rotation Heat Pump is explained in a first step while also other methods to calculate the cycle by using Enthalpy and numerical methods are following. Because the Joule cycle is almost independent of the temperature level present in a heat pump, a change of source and sink temperature influences the COP only in a little way. To demonstrate the flexibility and how it effects the cycle when thermal power changes, different operating points are shown and explained. This is also pictured in results of test data for a final built RHP. Besides the named differences, very important for the process is the used fluid which is a mixture of noble gases, has no Global Warming Potential (GWP) as well as the ODP (Ozone Depletion Potential) is zero. The main components are Helium (He), Argon (Ar) and Krypton (Kr) which are mixed in a ration optimal for the thermodynamic cycle. This is essential to tackle the global warming by reducing direct emissions. Further, this mixture of noble gases is not flammable and not toxic which is a big advantage in terms of the necessary safety systems for an installation.

2. BASIC PRINCIPLE AND FUNDAMENTAL CALCULATIONS

One of the fundamental differences between a Rotation Heat Pump and a conventional heat pump is the thermodynamic cycle. In contrast to the two-phase process, which is based on the Carnot cycle as an idealised process, the Joule process is implemented in an RHP. In a heat pump, the Joule process describes the counter clockwise circular process in a closed system, whereby the working gas never condenses or evaporates, but always remains in a gaseous state. In Figure 1 these two processes are compared schematically where the conventional system is static and the process of the RHP is rotating.

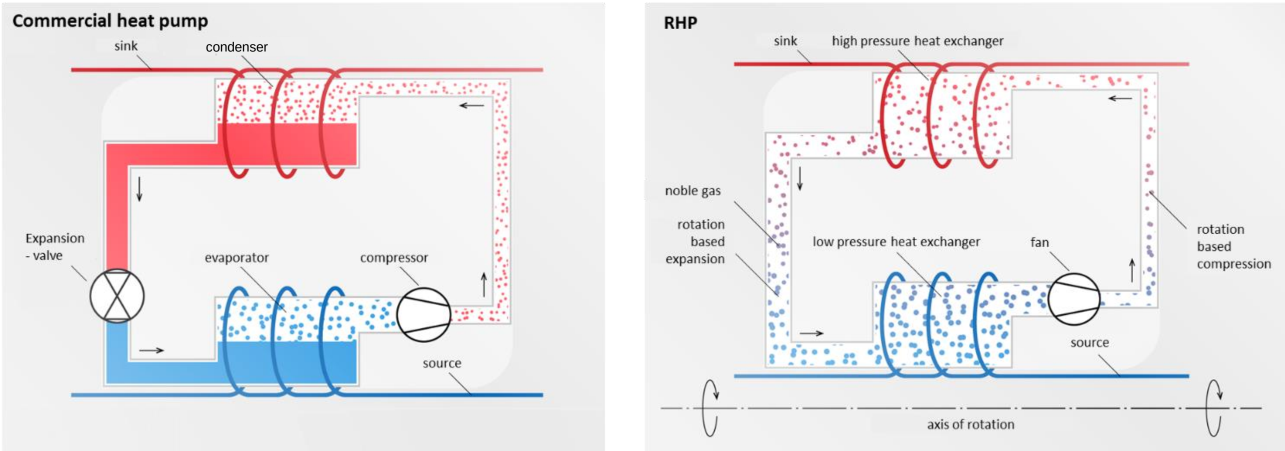

Figure 1: Basic principle of a Rotation Heat Pump compared to a conventional heat pump

However, in order to implement the Joule process in an economically viable manner, highly efficient compression of the working gas is necessary. This is achieved in an RHP by centrifugal forces. The rotation of a rotor filled with the working fluid causes the temperature of the fluid to rise towards the outside as the working gas is compressed. The T-s-Diagram of this concept is shown in Figure 2. Basic elements are the heat exchangers, both high and low pressure, the compression and expansion lines and the fan. These components are flowed through by the working gas and finally form the thermodynamic cycle.

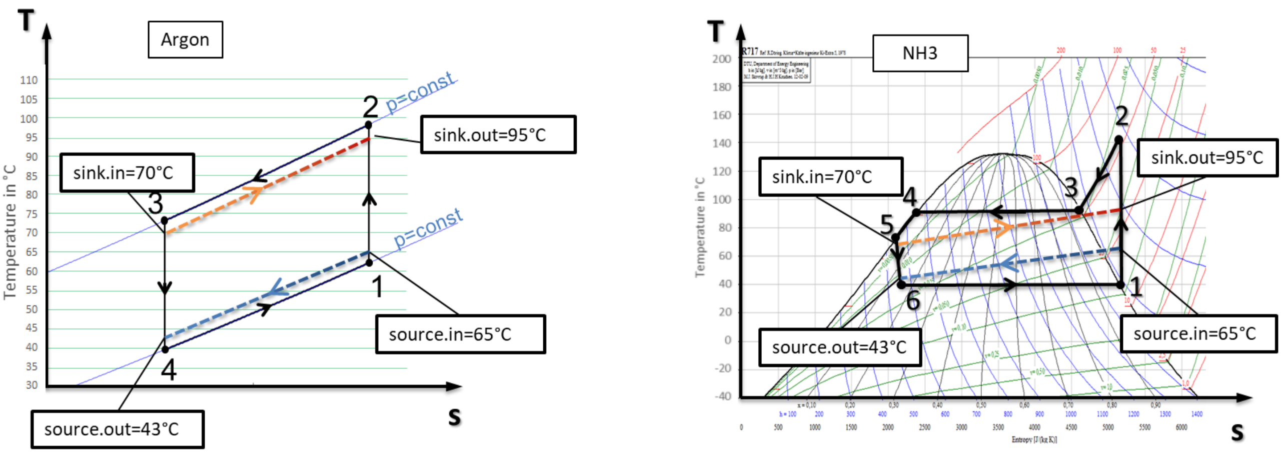

Figure 2: Counter clockwise Joule Process demonstrated with Argon (left) and example for a 2-phase Process realised with Ammonia (NH_3) – right, Adler et al., 2011

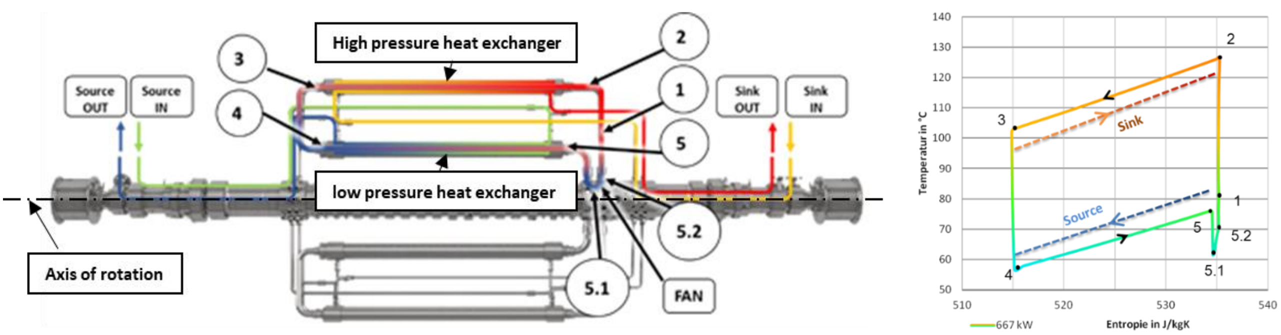

Figure 3: Design and structure of an RHP (left) and associated Joule process (right)

Figure 3 (left) shows the basic design including the heat exchangers and pipe system. The thermodynamic cycle is shown in Figure 3 (right) based on CFD (Computational Fluid Dynamics) calculations. The temperatures are given here only as an example, the process can be implemented flexibly at different temperature levels. While most applications use a compressor to increase pressure and temperature, which efficiency is essential for the COP of the system, the main compression in an RHP is based on a centrifugal potential. This is the key factor which leads to a very high efficiency of the cycle, for the main compression of the gas only frictional losses based on the relative flow velocity in the system have to be compensated. These little losses result in a compression efficiency of more than 99% for the compression pipes. Due to the advantages of the gaseous working fluid of the Rotation Heat Pump, compared to compression heat pumps, it is possible to cover a wide temperature range (-20 to +150°C) with an almost constant high COP. This means that a heat pump can also achieve a very high degree of flexibility, which has not been available in this form before. This enables the use in many applications where heat pumps couldn't be used till now. Those are for example drying of bricks and food (at different temperature levels) as well as district heating applications with high supply temperatures.

2.1. Calculation based on the centrifugal potential

As mentioned above, the first method for calculating the Joule Process in a Rotation Heat Pump is based on the centrifugal potential ϕ_{Zf} in m^2s^{-2} written as

$$\phi_{Zf} = \frac{\omega^2 r^2}{2} \qquad \text{Eq. (1)}$$

for compressing and increasing the temperature of the working fluid. It is similar to the gravitation potential between two masses. The centrifugal potential basically depends on the rotational speed ω in s^{-1} and the radius r in m where the energy of ϕ_{Zf} written as

$$E_{Zf} = \frac{m\omega^2 r^2}{2} \qquad \text{Eq. (2)}$$

regards the input of the mass in kg. The correlation of pressure in a closed rotating system for a fluid with the density ρ in kg/m^3 with respect to the radius and constant rotational speed can be written as

$$p_{(r)} = \frac{\rho_{(p,T)}\omega^2 r^2}{2} + p_0 \qquad \text{Eq. (3)}$$

where the static pressure in the system is included by p_0 in Pa and is based on the centrifugal potential where the variation of density over pressure and temperature is essential for this application. Having gas properties for density and a given point to start, the compression can simplified be calculated via an isentropic compression process. This means using the static pressure p_0, rotational speed and the radius of interest (r_1, r_2) the pressure (p_1, p_2) at specific points can be calculated. Using further the formulation for isentropic compression

$$T_2 = T_1 \left(\frac{p_1}{p_2}\right)^{\frac{1-\kappa}{\kappa}} \qquad \text{Eq. (4)}$$

the temperature at e.g. point 2 can be evaluated. Since pressure and temperature are always influencing density, some iterations may be necessary. The isentropic exponent for a monatomic inert gas can be assumed as 1.66, as a further simplification for a first calculation. Using these formulations, the calculation of the centrifugal based compression is possible only needing a few parameters. An advanced option to find a more detailed result is including the compressibility factor and corresponding derivations which is not explained here in detail.

2.2. Calculation based on Enthalpy and real gas properties

A further method for calculating the temperature lift is the usage of the Enthalpy, which is representative for the internal energy of the system. Starting with the first law of thermodynamics for stationary processes

$$\dot{Q} + \dot{W}_t + \dot{m} * \left(h_e - h_a + g * z_e - g * z_a + \frac{1}{2}c_e^2 - \frac{1}{2}c_a^2\right) = 0 \qquad \text{Eq. (5)}$$

assuming the heat transfer $\dot{Q}$ and the work $\dot{W}_t$ transferred over system boundaries are zero, the mass flow is not relevant anymore. Further, the relative velocities c_e and c_a are equal because they describe the internal flow velocity in the system which is almost constant in a compression pipe. In a next step the potential energy can be described as the acceleration g multiplied with the height z, where g can be written as the radius r times rotational velocity ω^2 and z is the radius r. Using this, the final equation is found as

$$h_{12} = \frac{\omega^2 r_2^2}{2} - \frac{\omega^2 r_1^2}{2} \qquad \text{Eq. (5)}$$

where the specific Enthalpy difference in J/kg describes the change in velocity. Having all parameters given for calculating h_{12} and a point where to start is defined with temperature and pressure also the Entropy can be evaluated. Again, assuming an isentropic compression and having real gas properties, the second point for the temperature and pressure increase is known when Entropy is kept constant.

2.3. Calculation based on Computational Fluid Dynamics (CFD)

A next possibility is the use of modern numerical calculation methods which can be used for evaluating the compression process. Therefore, commercial software was used to analyse, demonstrate and compare the different results of the compression. The implementation of adequate fluid data is essential for this form of calculating the process. In the shown case, the gas was modelled using the formulation of Redlich-Kwong-Soave. In Figure 4 the thermodynamic process based on a CFD-Simulation is shown for the whole cycle.

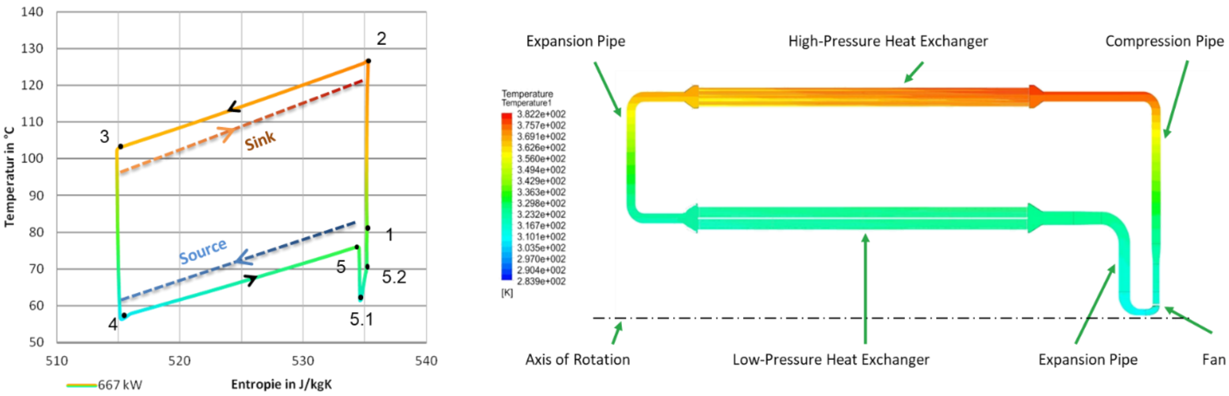

Figure 4: CFD-Simulation of the Joule Cycle in a Rotation Heat Pump

The possible maximum values of temperature and pressure for the RHP depend mainly on the mechanical restrictions of the system and not on the thermodynamics. Furthermore, high absolute velocities are reached at the outer diameter of the rotor while the relative velocity of the fluid inside the pipes is low and therefore the flow-losses are respectively small. Main drivers of losses for the Joule Cycle in a RHP are the bearings of the rotor, ventilation losses of the rotor in the housing and the mentioned flow losses. Besides this, the final COP of the machinery is depending on the divergence of the isobars, which determine the electrical power consumption of the ventilation system in combination with the compression efficiency of this component. Figure 4 shows where the fan is located in the process (between 5.1 and 5.2.).

3. FLEXIBILITY AND OPERATING POINTS

To show the flexibility of the process different operating points have been simulated with CFD-Software and can be compared with analytical data. The following Figure 5 shows on the one hand side different application cases simulated with full 3D-CFD methods for different pressure, temperature and thermal power levels and on the other hand an analytical calculation for one point. The simulation cases show that the heat transferred at the sink and source relates to the specific change in Entropy when mass flow is kept constant. While for the temperature lift the rotational speed is essential, which is shown by the "height" of the processes, the divergence of the isobars is increasing when

- transferring more thermal power
- increasing the temperature lift

which is an important point when calculating the COP using the electrical power consumption of the fan. Because the fan is the main component for electrical power consumption it is very important to keep the pressure increase and mass flow as low as possible for a certain operation point. For changing conditions of the static pressure in the system which may be realised by changing the initial pressure, the level of the shown curves change at the same time. Of course, the fluid properties like density, specific heat capacity, viscosity and so on change as well when this pressure is adjusted. So, regarding the former calculation where the density is included, it is obvious that the whole process is moved to a certain temperature or pressure level but doesn't change in general.

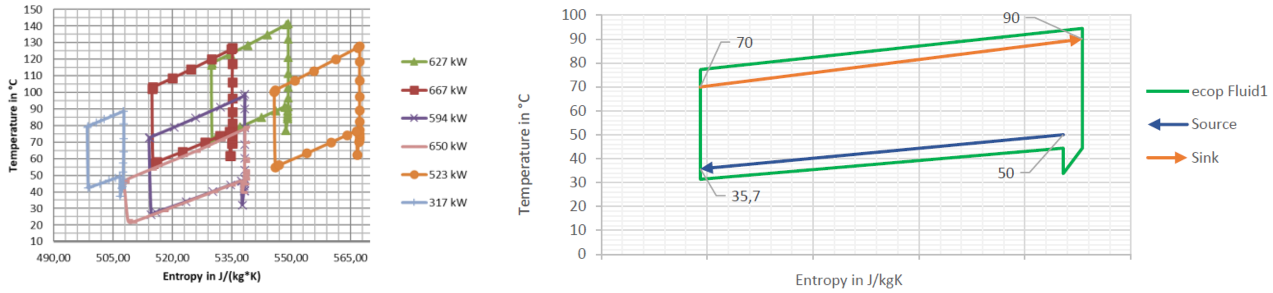

Figure 5: Different operating points evaluated by CFD-Simulations (left), analytical calculation with respect to test-data (Adler et al., 2017)

4. REFERENCE SYSTEM AND TEST DATA

Since the first reference System has already been successfully implemented, first test data is available and is shown in the following section based on Längauer et al. (2019). Figure 6 shows the final arrangement of the Rotation Heat Pump where in the left control cabinet the power supply, in the right cabinet the control unit and in the mid part the rotor and housing are located. For a RHP-K7, which was used in the test, the nominal thermal power output at the sink is determined with 700 kW where also part load up to around 50% is possible. An example for the flexibility is shown by the following diagrams, which display temperature and COP over time measured in combination with a test rig where the temperature and mass flow can be adjusted easily. The temperatures show a shift from around 70°C to 90°C at the sink and an equivalent temperature profile at a lower level for the source. This is caused by the arrangement of heat exchangers on the test rig to recover as much heat as possible. Besides this, it is also shown that the COP remains almost constant during this shift. It shows exactly the advantage of the Joule cycle for a heat pump, the process and also the COP are not coupled to a certain temperature level and can be realised at different temperatures without increasing losses.

Figure 6: Reference system of a Rotation Heat Pump and test results based on Längauer et al. (2019)

5. CONCLUSIONS

The main principle of a Rotation Heat Pump has been analysed in terms of fundamental thermodynamic and physical points of view. The calculation of temperature spread according to the rotational speed of the rotor has been introduced by using the centrifugal potential and basic thermodynamics. The given formulations allow the calculation of the thermodynamic cycle in a Rotation Heat Pump, where it has been clearly shown that real gas properties are necessary for an accurate result. For first estimations simplifications and assumptions may also work but always show a deviation. To compare analytical methods also 3D-CFD models has been calculated and show good accordance when detailed gas properties are used in the numerical simulation. By using the given formulations and numerical models different operating cases where evaluated and show the differences in the T-s-Diagram for varying boundary conditions. Further work would evaluate exact data and tables for the entire cycle and compare different inert gases or mixtures of gases.

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REFERENCES

Adler B. et al., 2011. Centrifugal compression turbo heat pump made by ECOP. 10th IEA Heat Pump Conference, Tokyo, Japan

Adler B., Mauthner R., 2017. Rotation Heat Pump (RHP). 12th IEA Heat Pump Conference, Rotterdam, Netherlands

Adler B., Mauthner R., Längauer A, 2017. Industrieller Einsatz einer Rotationswärmepumpe. DKV-Tagung, Bremen, Germany, Presentation

Längauer A, Adler B., Rakusch Ch., 2019. Testergebnisse einer Rotation Heat Pump. DKV-Tagung, Ulm, Germany

Längauer A, Adler B., Rakusch Ch., 2019. COP tests of a Rotation Heat Pump. ICR International Conference of Refrigeration, Montreal, Canada