



Rotation Heat Pump (RHP)

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Abstract

The use of heat pumps for high temperatures in the industry is nowadays limited by refrigerant and by oil of the compressor. Another not always considered fact is sensible heat (sliding temperature of medium during heat flow) at source and sink (s&s). In many applications (e.g. district heating and drying processes) supercritical heat pump processes fix this at heat sink but with rarely inflexible temperature changes.

Flexible temperatures at s&s without any modifications, temperatures up to 150°C and sensible heat transfers at s&s are possible by using a Joule process. This kind of process works profitable only if the compression and expansion is realized with very high efficiencies (>99%). ecop realises these efficient pressure changes in a rotating system by using centrifugal force instead of high flow speed like in common turbo compressors. The COP depends, similar to two-phase heat pumps, on temperature spread but rarely on temperature level. Due sliding temperatures at s&s the potential will always be better than Clausius Ranking or super critical cycles. The used working gas, extracted from air, has no climate potential, isn't flammable and is natural.

In summary the RHP has wide coverage of temperature, ecologically friendly working gas and higher COP as two phase circles. In industries waste heat is mostly sensible, so these are ideal circumstances for a RHP or just using it for higher temperatures. Measurements verified the realization of high COP for the considered applications.

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Selection and/or peer-review under responsibility of the organizers of the 12th IEA Heat Pump Conference 2017.

Keywords: Rotation Heat Pump, Industrial, high temperatures, ecop, flexible

1. Introduction

Since the last paper from ecop Technologies GmbH with the title "Heat pump for Process Industry"[1], at the Heat pump Conference 2014 in Montreal, there has been a lot of improvement in the machine. The function principle of the Rotation Heat Pump (RHP) is still the same, so after a short summary of the functionality, this paper will discuss the specific values of the current heat pump (Pilot of RHP type K7 with 700kW heating capacity) in different operating modes. With the Rotation Heat Pump technology, ecop showed that it is possible to realize a heat pump process based on a counterclockwise joule cycle (also known as Joule-Brayton or Brayton cycle) which has a better COP than a two phase cycle heat pump process, depending on certain circumstances. The following tables show the reason why there are hardly any heat pumps using a Joule process. For the calculation in Table: 1 is an ideal Joule and a counterclockwise Clausius Rankin cycle with a heating capacity of 1MW at the sink side. In Table: 2 we look at the same cycle, but instead of 100% efficiency of compression and expansion it is shown with 80% (expansion just at the). The level of source temperature is (65-43°C) and at the sink side is (70-95°C). The temperature difference is 3K between working gas/refrigerant and sink/source flow. The fluid values from the whole paper are from the NIST Database [2].

Table: 1 COP potential of a Joule process and 2 phase process with NH3

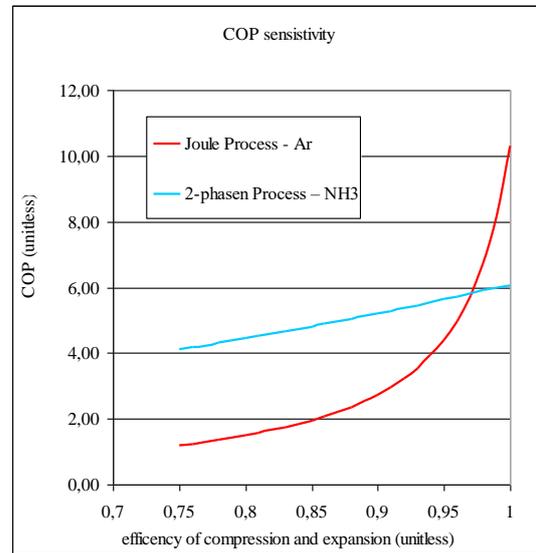
Compression with	Joule process – Ar	2-phase process – NH3
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100% efficiency @ 1MW heat emission		
P.compression in kW	1319	165
P.expansion in kW	1222	-
Power deviation	97	165
COP	10.3	6.1

Table: 2 Decrease of COP

Compression with 80% efficiency @ 1MW heat emission	Joule process – Ar	2-phases process – NH3
P.compression in kW (80% efficiency)	1649	207
P.expansion in kW (80% efficiency)	978	-
Power deviation	671	207
COP	1,49	4.8

Fig.: 1 shows the influence of a lower compressor and expansion efficiency to the COP. The lines end at 0,75 because with a lower efficiency, the loss in the Joule process is higher than the heat sink capacity. With a lower efficiency the mass flow has to decrease, otherwise the heat emission is higher than 1MW. The interesting fact is, that with a higher efficiency than 0.96 in compression and expansion, the Joule process gets better and better than the conventional process for this boundary conditions. This is the reason why it wasn't possible in the past to realize a Joule process with a better COP than two phase process, if there is a useable refrigerant at this temperature level for the two phase cycle.



With this new possibility of this Joule process, there are three more useful facts, which can give a huge advantage in different applications compared to a two phase cycle.

Fig.: 1 Decrease of COP in affect of efficiency of pressure change

1. a better approach in both heat exchangers because heat transfer at sink and source are often sensible
2. flexibility in temperature levels
3. higher temperatures from sink and source

1.1. Sensible Heat Exchange

Because the working fluid is always gaseous and never liquid during the cycle, it never comes to a phase change and so to a non sensible heat change. Through that there is always a temperature change during heat exchange. In the industry sink and source are often sensible too, so with the same heat capacity flow on both sides (working fluid and source/sink fluid) the temperature difference is identical along the heat exchanger. With

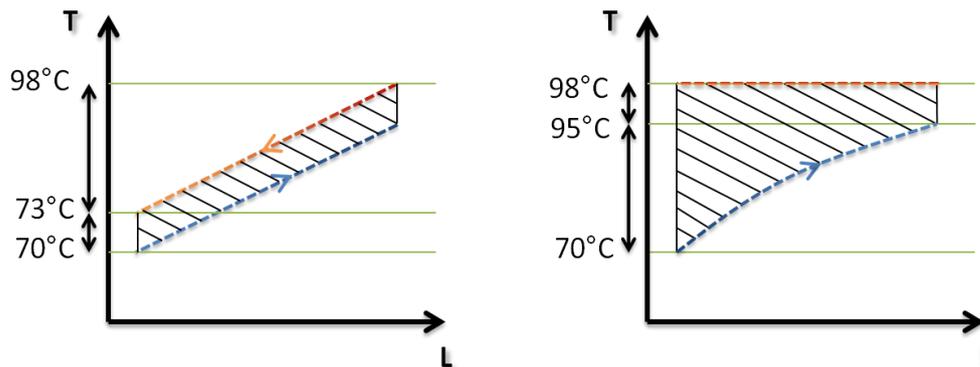


Fig.: 2 Exergy loss in a heat exchanger

$\Delta T_m = 8,4K$

a small average temperature between working gas/refrigerant and other fluid the exergy loss in the heat exchanger is lower, and affects positive to the COP. In Fig.: 2 is shown the changing space between the two temperature curves. On the left side both medium are sensible on the right side just the colder medium is sensible the other one is changing the phase. The middle temperature difference (ΔT_m) for the left heat transfer in Fig.: 2 is simple 3K. ΔT_m of the right heat transfer get calculated with (1)

$$e_v = \frac{\Delta T_{left} - \Delta T_{right}}{\ln\left(\frac{\Delta T_{left}}{\Delta T_{right}}\right)} = \frac{28 - 3}{\ln\left(\frac{28}{3}\right)} = 8.4K \quad (1)$$

The exergy loss relating to 20°C is for the left side of the picture 3,8% and for the right side 17%. The result comes from following equations. Equation (2) shows the specific exergy flow for a heat flow.

$$e_v = \left(1 - \frac{T_U}{T_m}\right) \cdot \dot{q} \quad (2)$$

T_U ... temperature of the environment

T_m ... the middle temperature of the heat flow

In an adiabatic heat exchanger the heat flow has to be the same for both mediums (blue and red line). So the efficiency from the exergy flow in the left part of Fig.: 2 the exergy efficiency can be calculated with equation (3). The middle Temperature of the heat flow can be calculated as arithmetic middle, cause the Temperature between both mediums are constant.

$$\eta_{e_left} = \frac{\left(1 - \frac{T_U}{T_{m2}}\right) \cdot \dot{q}}{\left(1 - \frac{T_U}{T_{m1}}\right) \cdot \dot{q}} = \frac{T_{m1} \cdot (T_{m2} - T_U)}{T_{m2} \cdot (T_{m1} - T_U)} \quad (3)$$

$$T_{m1} = \frac{98 + 73}{2} + 273 = 358.5K \quad (4)$$

$$T_{m2} = \frac{95 + 70}{2} + 273 = 355.5K \quad (5)$$

The exergy loss for the heat exchange in Fig.: 2 is analog to equation (3). T_{m1} get replaced with T_{m3} and T_{m2} with T_{m4} . In Fact of the logarithmic curve, T_{m4} can be calculated like in equation (7)

$$T_{m3} = \frac{98 + 98}{2} + 273 = 371K \quad (6)$$

$$T_{m4} = \frac{95 - 70}{2} + 273 = 355.5K \quad (7)$$

Equation (3) shows a exergy loss from 3,8% for the left heat exchanger and for the right one we get an exergy loss from 16,4%.

1.2. Flexibility in Temperature Level Change

From time to time it's very useful, if the level temperature of the heat pump can be changed easily. For example in consequence of seasons. Changes of the temperature level, are also possible with two phase cycles, but many process parameters change more than in a Joule process. A very critical characteristic thing is especially the high pressure which rises from 54,4 bar up to 91,95 bar (compare with Table 1). More interesting is the change of the volumetric flow of the compressor inlet – increase around 42%. Without any modification the RHP with the Joule cycle can be used on a wide band of temperature level (compare with Fig.: 3), of course with limits based on design temperature of the mechanical parts of the machine.

Table 1: Effect of Changed Temperature Level

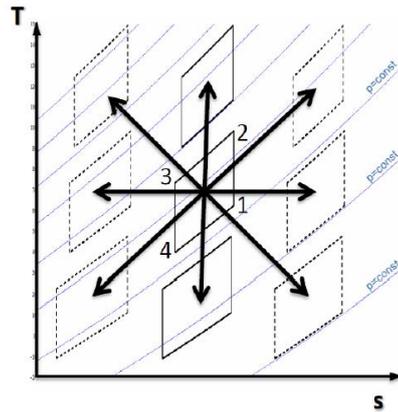


Fig.: 3 Flexibility of a Joule Process

2-phase process -NH₃	Case 1	Case 2	change in %
	sink 70/95 in °C source 65/43 in °C	sink 100/125 in °C source 95/73 in °C	
\dot{m} in kg/s	0,9	1,13	25
$\dot{V}_{compressor.inlet}$ in m ³ /s	0,0708	0,0407	42,5
p_{max} in bar	54,4	91,95	69
$\dot{Q}_{overheater}$ in kW	191,8	304,2	58,6
$\dot{Q}_{condenser}$ in kW	702,4	533,5	24
$\dot{Q}_{undercoole}$ in kW	105,8	162,3	53,4
Compression ratio	3,31	2,651	19,9
COP*	6,05	6,33	4,5
Joule process with argon	sink 70/95 in °C source 65/43 in °C	sink 100/125 in °C source 95/73 in °C	change in %
\dot{m} in kg/s	71,07	71,74	0,9
\dot{V} in m ³ /s	1,16	1,175	1,2
p_{max} in bar	54,4	59,14	8,7
\dot{Q} in kW	1000	1000	0
Compression ratio	1,290	1,265	1,9
COP*	10,3	11,24	8,4

*For this calculation there is a $\Delta T=3K$ gap between sink/source and working gas/refrigerant, and also a ideal heat pump cycle. The reason for higher COP in the second case, is the higher middle temperature of the source.

1.3. Higher Temperatures

In a two phase cycle, there can be problems in consequence of the stability of the oil or refrigerant. The RHP technology works instead within the main compression without relative moving parts and so without oil or grease. The working gas is a natural inert gas mixture so there is no limitation concerning stability. For the bearing of the fan there is grease necessary too, but due to the fact that the working gas flow doesn't touch the oil and is located in a low temperature area in the machine, there are no problems with segregations or stability, and the spectrum of useable grease is much bigger.

2. Functional Principle

The whole thermodynamic cycle can be compared with a Joule process. A Joule process contains two isentropic and two isobaric change of state which are alternating. Compare doesn't mean a 100% fit, because there is a extra change of state before the isentropic compression. The whole compression includes the main high efficient compression (~90%) and a classic compression with a fan (Step 5 to 2)

The whole RHP is based on 5 steps. The single steps of the thermodynamic circle are shown in Fig. 4, the five steps get explained below. Friction happens of course during every single change, but the dimension is different and not extra mentioned.

- Step 1 from point 1 to 2

The working gas get compressed very efficiently. During this compression the working gas get warmer. The power for compression work comes from step 3 (expansion 3 to 4).

- Step 2 from point 2 to 3

In the high pressure heat exchanger the working gas delivers heat to the sink, and during this step, the working gas gets colder and the flow of the sink gets warmer.

- Step 3 from point 3 to 4

In this process step the working gas gets expanded, so that the working gas cools down, the release power (torque and rotation) is equal to the compression in "point 1 to 2"

- Step 4 from point 4 to 5

In this step, the working gas takes the heat from the heat source.

- Step 5 from point 5 to 1

The compression works in step 1, is covered from step 3. The rest of the compression for the whole cycle and the whole losses of friction must be delivered from the fan, which happened in this step. The main gap between compression (5-2) and expanding power (3-4) comes from the divergence of the isobar change of state.

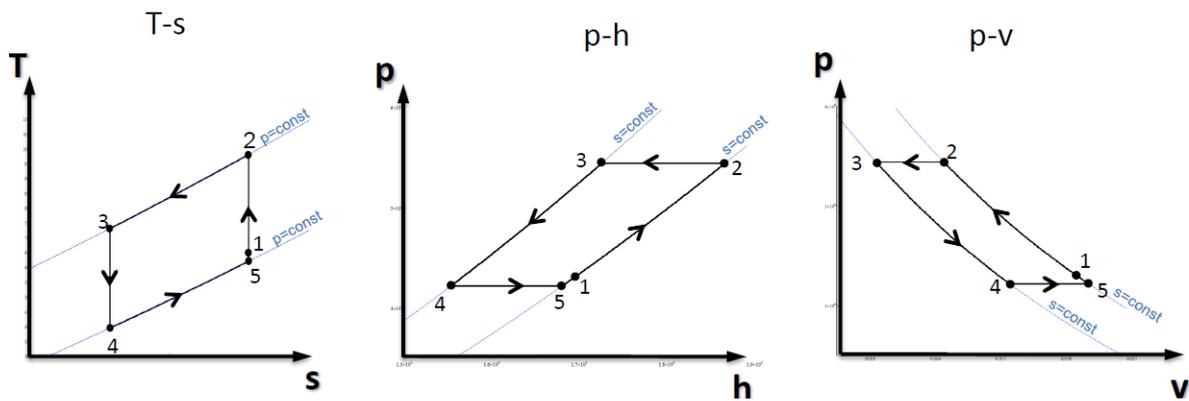


Fig. 4 RHP Process in different Diagrams

The reason for the very high pressure change in step 1 and step 3 are the relative low velocity of the gas flow and with that the friction especially between gas and wall is low. Fig.: 5 shows the pressure change of a water column. The pressure gets linear higher in fact of the incompressible of water.

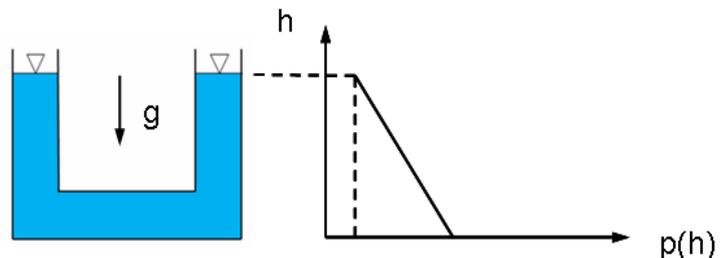


Fig.: 5 Pressure change in consequence of gravitation

Following thought experience should help to understand this process (Fig.: 6).

When you put a water filled tube from sea level down to the Mariana Trench in the Pacific Ocean and back to sea level, the pressure in the tube rises up to the maximum on the sea ground and back to the beginning pressure on the way up.

The first extra water drop on one side will push the whole water column a small way further trough the tube. Every further drop continues this process and so all the water drops are going along the tube and getting compressed to the bottom and expand on the way up nearly 100% reversible.

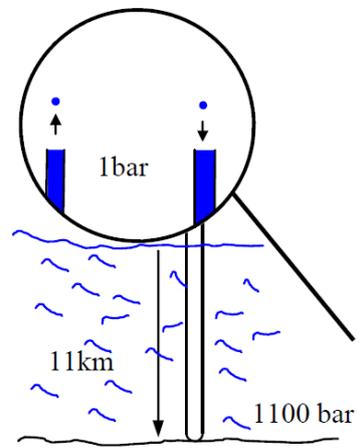


Fig.: 6 Tube to Mariana Trench

The same principle is used in the RHP with the difference, that instead of the gravitation the centrifugal force changes the pressure. Fig.: 7 shows the pressure change in the RHP of the compressible gas. Due to the fact of the compressibility and the centrifugal force which increases with the power of 2 in according of the radius the pressure change is not a linear. Fig.: 7 shows the Joule process realized within the Rotation Heat Pump. This RHP is the predecessor of the K7 which has just a tenth of the heat power of the K7. It's also connecting the above shown diagrams to the realization.

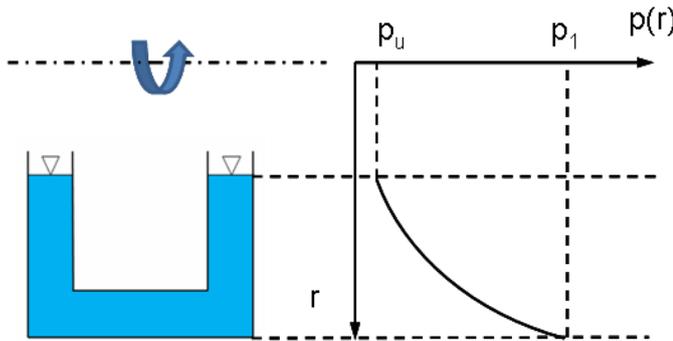
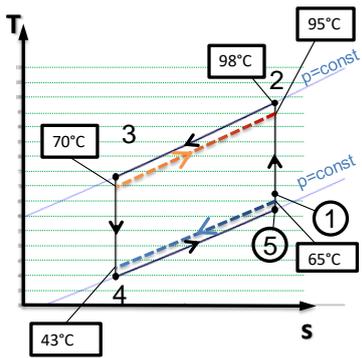


Fig.: 7 Pressure change in consequence of centrifugal force



- 1 – 2 isentropic compression
- 2 – 3 isobaric heat tra
- 3 – 4 isentropic expan
- 4 – 5 isobaric heat tra
- 5 – 1 isentropic comp

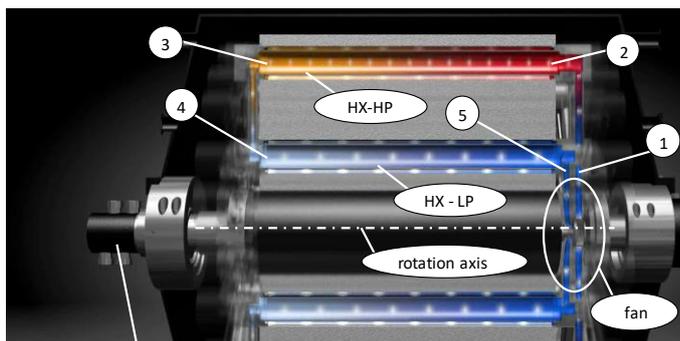


Fig.: 8 Joule process within the Rotation Heat Pump ©

3. Facts about

RHP K7

Fig.: 9 Fig.: 9 shows the RHP K7 pilot ready to ship and in



Fig.: 9 Implemented RHP K7 Pilot at Biomass Heating Plant©

Table: 3 there are some facts about the realization of a Rotation Heat Pump.

Table: 3 Facts about RHP K7

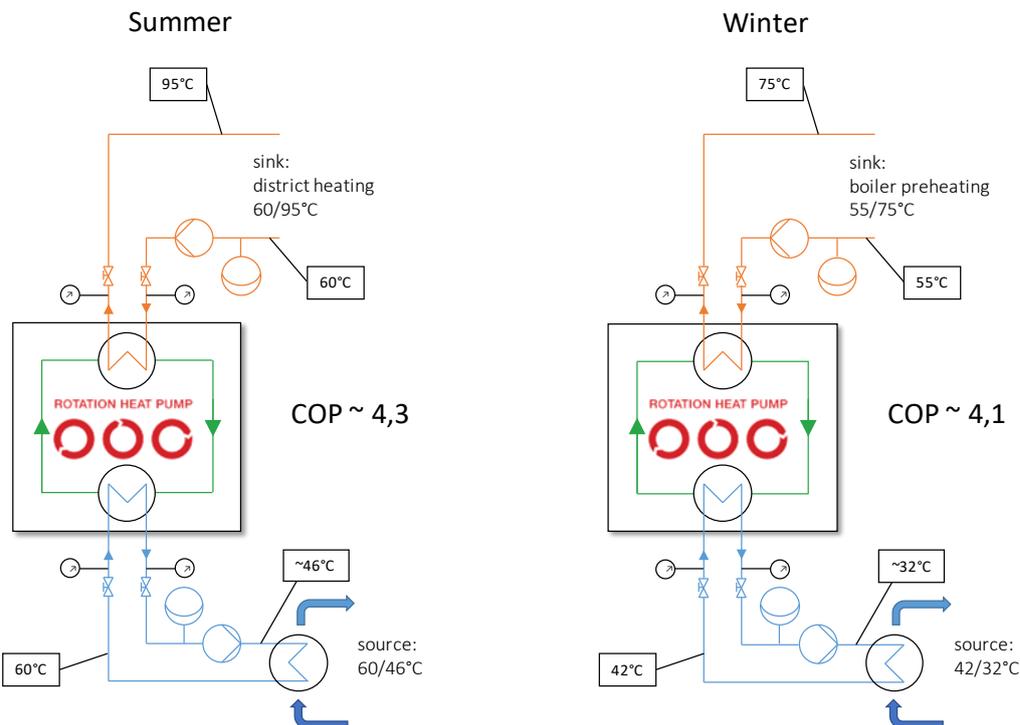
Technical data	
Weight:	15t
Dimensions (W x H x L):	2400 x 2500 x 7000mm
Connection heat source:	DN80 (3")
Connection heat sink:	DN80 (3")
Maximum flow temperature on heat sink:	150°C
Maximum flow temperature on heat source:	110°C
Maximum temperature spread between sink out and source in:	40 °C
Minimum flow temperature:	-20°C
Designed heat transfer medium:	H ₂ O
Heat output:	400-700 kW
Working gas	ecop Fluid 1 (inert gas)
Nominal heating water flow rate / pressure drop:	21m ³ /h / 0,5bar
Main supply:	400V-3-N ~50Hz
Nominal power consumption:	70 - 280kW

3.1. Implementation of RHP K7 Pilot

The Implementation of the RHP K7 pilot is in a biomass heating plant near to Vienna. Because of the flexible temperature level it can be used in summer and winter. The calculation is based on 4500 operating hours in winter and 2500 operating hours in summer. Because of the flexibility of the Joule Process the heat pump can be used the whole year. So the useable heat energy in summer is 1600 MWh and 2880 MWh in winter: The return of Investment is 55% higher than without summer operating.

3.1.1. District Heating

The following schema (Fig.: 10) shows the implantation of the RHP K7 pilot. The heat pump is a part of the heat producer of a 14MW grid.



The advantages at the implementation which are shown in Fig.: 11 and give a little bit more of information about whole district heating system:

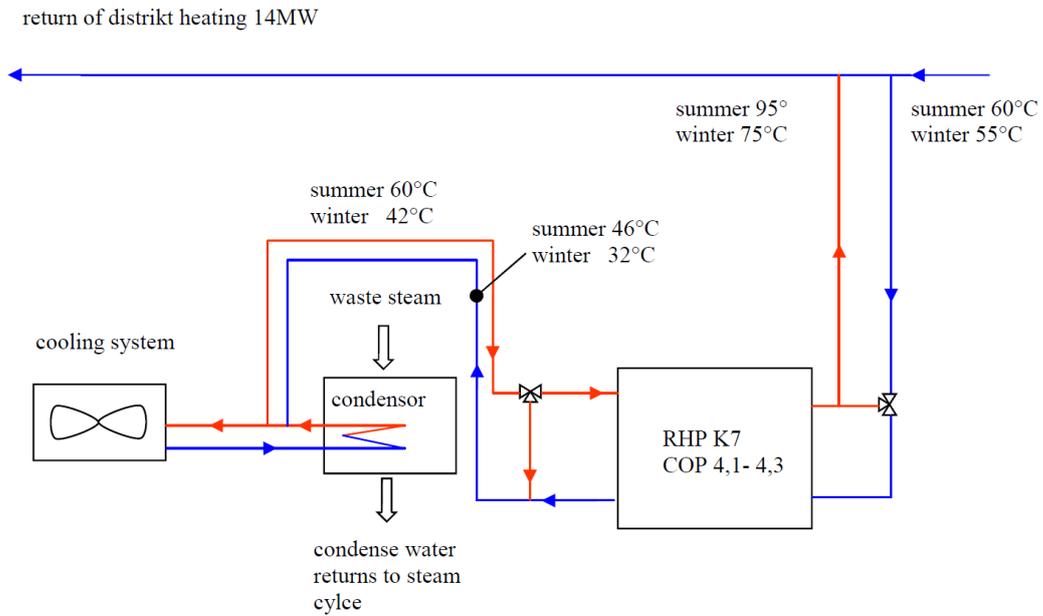
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Fig.: 10 Implementation of RHP K7 pilot

- g the heat from the waste steam
- reducing the electricity for the fans in the cooling system, of course needs the K7 also electricity.
- potential for reducing the pressure of the condenser for a higher electricity output

3.1.2. Alternative Application Spectrum

Fig.: 11 Implementation RHP K7



The range where the RHP K7 can be implemented is very wide. The following examples show

some of them. All the counted cases in Table: 4 Spectrum of RHP K7 are shown in Fig. 12 and can be realized with the identical constructed heat pump without any changes.

Table: 4 Spectrum of RHP K7

Case	Application	Source	Source in °C	Sink	Sink in °C	COP
#1	all season district heating	extern heat source	60/30	district heating	60/100	5,5
#2	summer district heating	lake water	20/2	district heating	55/70	3,7
#3	Summer district heating (waste heat from boiler)	waste heat boiler	60/46	district heating	60/95	4,3
#4	winter district heating	flue gas condensation	55/30	district heating	55/75	5,8
#5	preheating of inlet district heating in winter (preheating inlet temperature)	waste heat boiler	42/32	preheating of inlet district heating	55/75	4,1
#6	wood drying	condensate from drying process	65/45	process heating	75/95	4,9

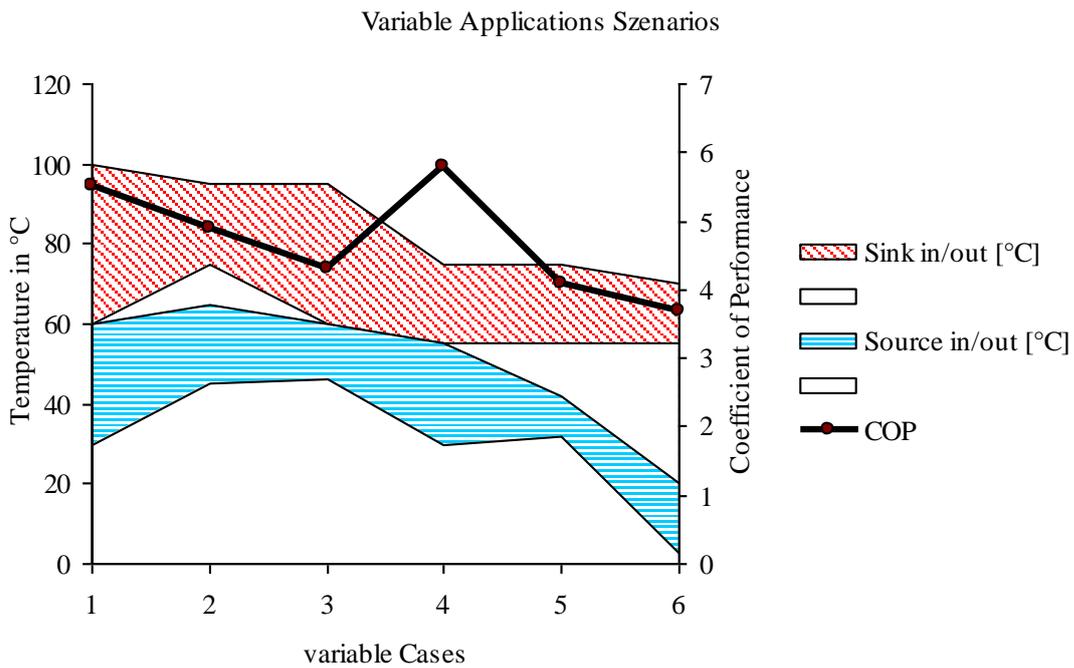


Fig. 12 visualization of example cases from table 4

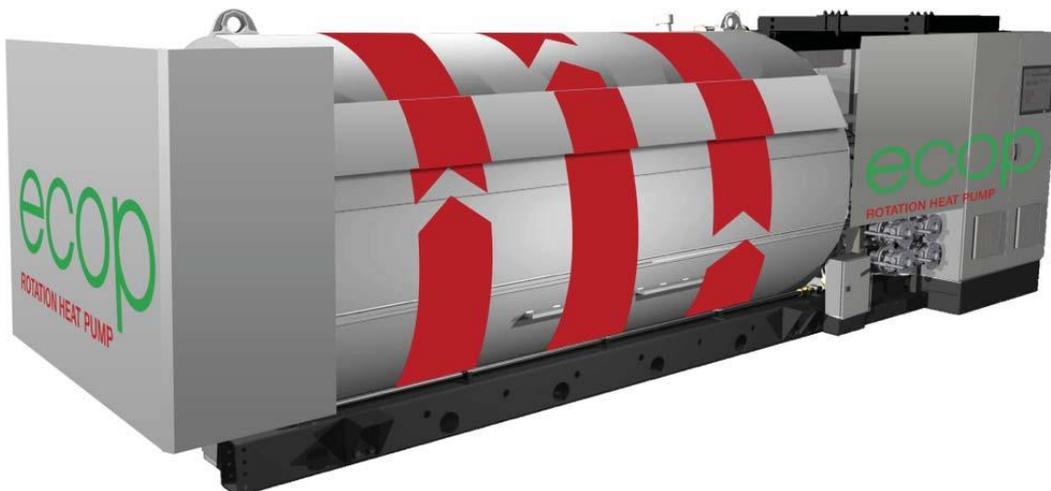
4. Conclusion and Future Outlook

A Heat Pump Process based on a Joule process brings positive effects which were not realizable with established compressors. For a efficient operation mode at a Joule process, everything stand or fall with a very high compression and expansion of the gas, which is always a gas and never liquid as in other heat pumps. It's also necessary to recover the main part of the power during the expansion. In the explained example of this paper (Table: 1), the recovered power from the expansion is approximately 20% higher than the heat for the sink.

The positive effects from a heat pump using the Joule process are:

- Flexibility of temperature level without changing any hardware on the machine,
- Higher possible COP when sink and source are sensible as a result of the lower exergy loss in the heat exchangers
- Temperatures up to 150°C with the actual Heat Pump from ecop (K7) at the sink are possible and also temperature rises up to 40K (ΔT sink out to source in). It is just limited by the material strength.

During testing of our prototype of the RHP K7, we implement improvements ready for serial production that is available from Q2/2017. The RHP K7 is shown in Fig.: 13. We ramp up the production in a new plant early



2017. The next step in product development is to build a RHP with a heating capacity of about 2MW.

Fig.: 13 Market Ready RHP K 7 ©

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