HEAT PUMP FOR PROCESS INDUSTRY

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Abstract: In contrary to the home and building sector heat pumps are not so well established in the industrial sector. Yet waste heat combined with heat pumps would open up a huge potential to substitute fossil fuels with only minimal exergy/ electrical energy usage. In addition to the significant positive impact on the environment, it leads directly to a reduction in operating costs. However recent studies have shown that higher temperatures of at least 100°C are needed in industries. Conventional heat pumps show limitations in flexibility and in achievable temperatures by the used technology. As a consequence of this such systems can often not be realized for such industrial usages.
ECOP developed now a break-through heat pump product. It is based on a Joule cycle with compression efficiency of up to 99.9% making a standardized product for applications of up to 150°C possible. Pressure and temperature of the working medium can be adjusted by a variable, oil free compressor resulting in a machine that can adapt to its ambient conditions, while reaching a high Coefficient of Performance (COP).
Heating above 70°C is the target application for the industrial heat pump. By using centrifugal forces the pressure and the temperature of the working fluid can be changed in a highly efficient way. Slow flow velocities within the system cause only minimal losses for most efficient compression efficiencies. Changes of the rotational speed enable a flexible temperature spread, allowing the technology to work in a highly flexible way operating at any temperature within the operation range of -20°C up to 150°C.

Key Words: Industrial, Heat Pump, flexible, High Temperature, ECOP

1 INTRODUCTION

In contrary to the space heat sector, heat pumps are not so well established in the industrial sector. Yet waste heat combined with heat pumps would open up a huge potential to substitute fossil fuels with only minimal exergy/ electrical energy usage. In addition to the significant positive impact on the environment, this leads directly to a reduction in operating costs.
However studies have shown that higher temperatures of at least 100°C are needed in industries. Conventional heat pumps show limitations in flexibility and in achievable temperatures by the used technology. As a consequence of this such systems can often not be realized for such industrial usages.
ECOP developed now a break-through heat pump product. It is based on a Joule cycle with compression efficiency of up to 99.9% making a standardized product for applications of up to 150°C possible. Pressure and temperature of the working medium can be adjusted by a variable, oil free compressor resulting in a machine that can adapt to its ambience conditions, while reaching a high Coefficient of Performance (COP).

2 TECHNOLOGY

Different technologies make it possible to realize a heat pump cycle. Within the compression heat pump technology a – at least partly - two phase region usage of the refrigerant is for sure the most common one. There is broad variety of refrigerants to realize this. Basically those refrigerants work as already mentioned, at least partly, in the two phase region in order to be able to use the stored latent heat. Machines with cycles that work in gaseous region only are known as well but so far solely used in special applications.
The problem about such single phase technology is today's efficiency of the change in state, especially the compression. The result so far was that the realizable COP is rather low compared with a two phase version, which tolerates lower efficiencies by using the latent heat and realizing a broader cycle. The usage of such a single phase cycle has promising advantages though, which might prove useful especially for process industry enviroment. As long as the working medium is in a gaseous state the machine could be used for different operation temperatures. Since a fluid like e.g. Nitrogen has the critical point at about 126K and is upwards gaseous, it means that the operation temperature would be barely limited by this. Another important point is the optimization of exergy losses in heat exchangers for applications where the sink and/or source fluids are single phased as well, as it is often the case within the process industry, when water, oil or air is used as heat transport medium.

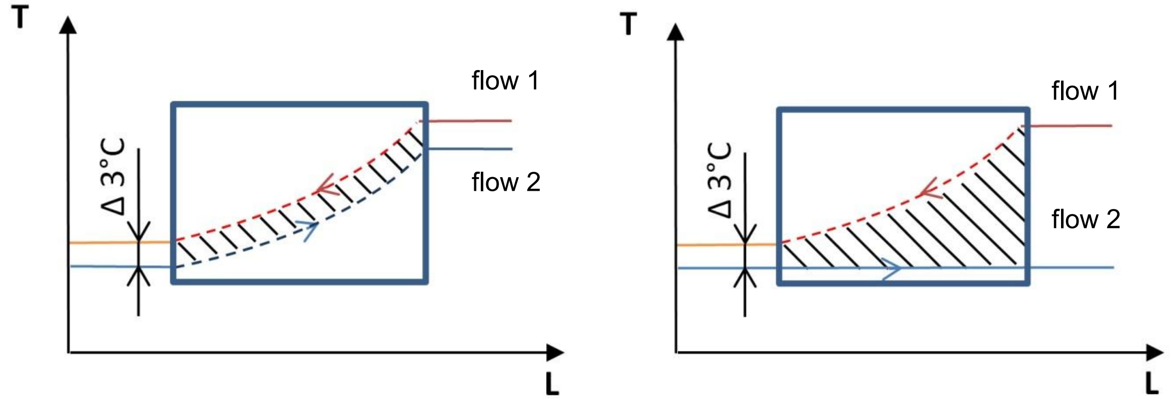

Figure 1: schematic exergy losses within heat exchangers for exemplary minimum Δ T 3°C

In the figure above exergy losses for in- and outlet temperatures in a heat exchanger are shown. Both diagrams illustrate a counter flow principal. The hot stream has sensible heat and is cooled down to a lower level. While the flow on the left has sensible heat too and changes the temperature significantly, the right flow uses latent heat (or a much higher massflow) resulting in a constant temperature. The shaded plain in between is proportional to the exergy losses, as shown in equation 1, and should be minimized.

$$d\dot{E}_L = T_A \cdot \frac{T_1 - T_2}{T_1 \cdot T_2} d\dot{Q} \quad (1)$$

Through increasing the compression efficiency significantly, e.g. above 98%, COPs of single phase region heat pumps would rise to a comparable level with two phase region heat pumps (Adler 2011). ECOP could realize a variable, oil free, high efficient compressor making it possible to realize an efficient Joule process and a machine that is able to adapt to its circumstances. This means that a heat pump could use waste heat at a high level and deliver the wanted output. If the temperature of the source changes, the machine could adopt through the variable compression to the new circumstances and deliver the same temperature output, though with a higher COP for rising source temperatures.

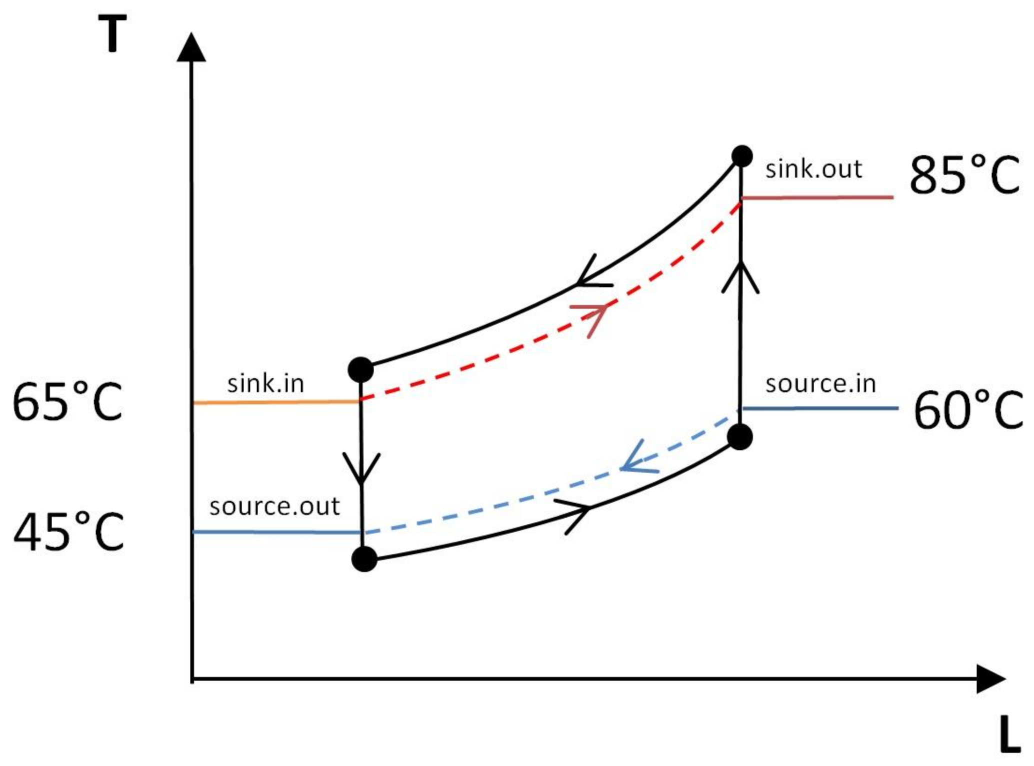

Figure 2: Implementation example

The cycle in Figure 2 shows a heat source usage of 60°C cooled down to 45°C. On the sink the 85°C output are delivered. With the shown Joule cycle a variable input temperature could be handled. If the temperature would rise from 60°C to 70°C and the cycle would not be controlled the output temperatures would rise as well. With a variable compressor ratio the output temperature could be adjusted back to 85°C. Since the Delta between the thermodynamic middle temperatures is smaller now, the COP rises.

2.1 Variable compression and expansion

The basic idea for this kind of compression is easy and can be seen every day in nature. The earth possesses an acceleration field causing aerostatic or hydrostatic pressure increase.

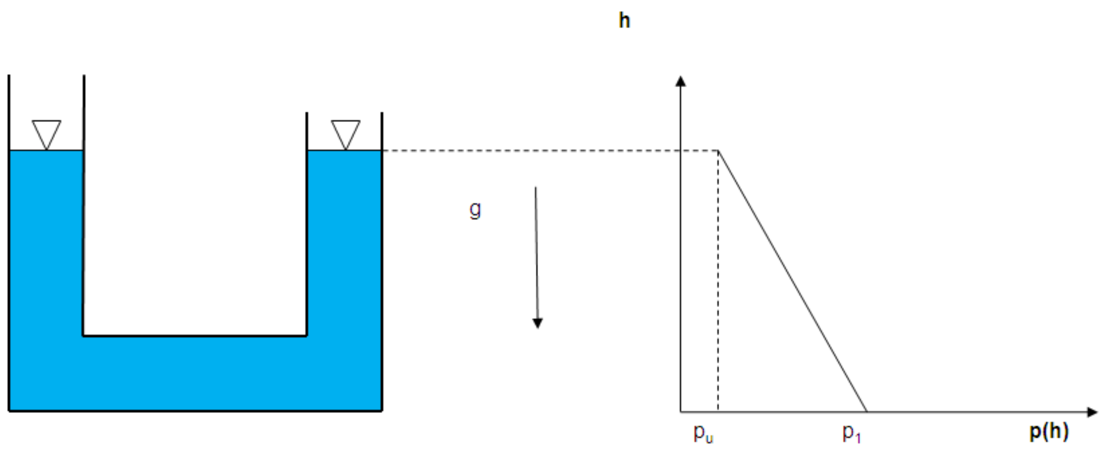

Figure 3: rising pressure through gravity

At the surface of the sea the pressure is around 100 kPa. For every meter below the surface the pressure is increasing. In 100 meter depth the pressure is around ten times as high as on the surface caused by the acceleration of the gravity force field.

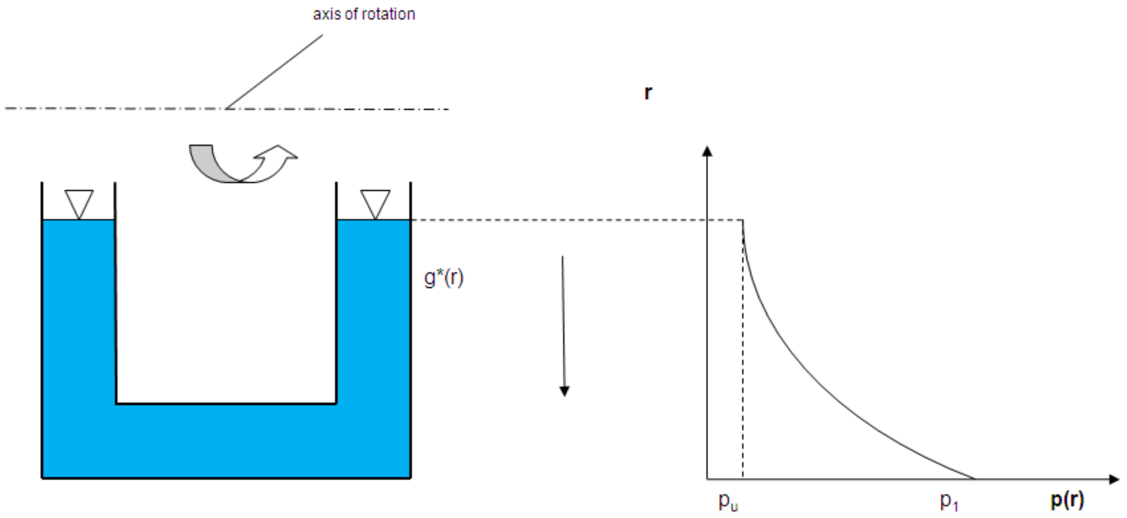

Figure 4: rising pressure through centrifugal acceleration

Of course this pressure increase also works if the gravitation (g) field is substituted by a centrifugal acceleration field, g*(r) caused by rotation. The centrifugal acceleration, which is depending on the radius and the angular velocity, causes a parabolic, instead of a linear, pressure increase.

2.2 Gaseous cycle

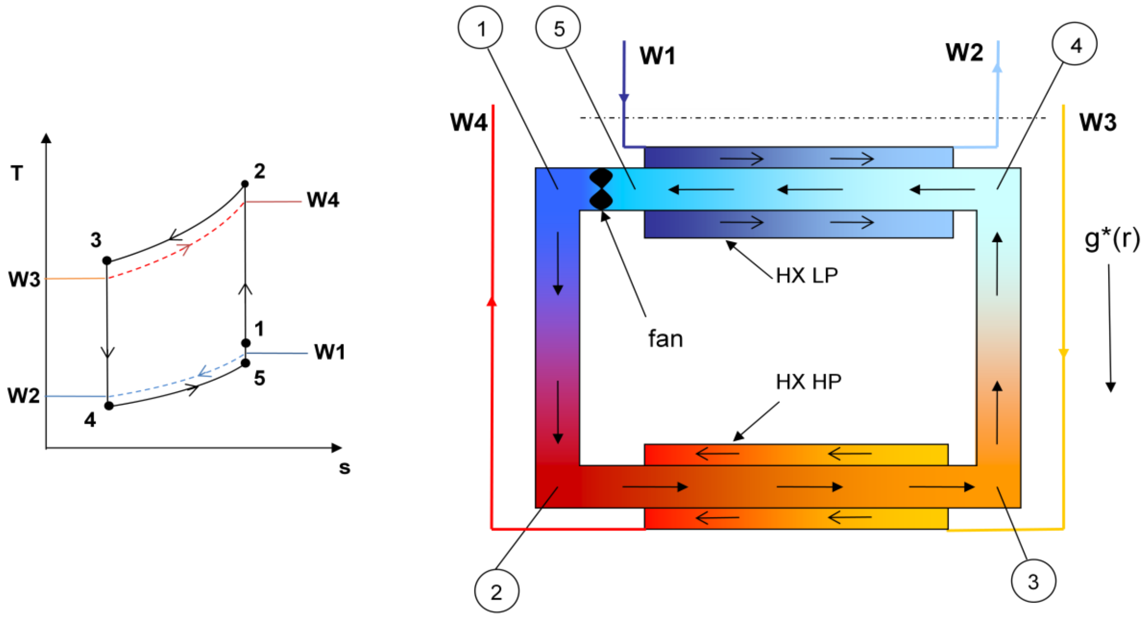

Figure 5: centrifugal compression heat pump cycle

When the U Pipe from Figure 4 is closed, a thermodynamic cycle can be realized in the way shown in Figure 5. The exemplary temperatures are according to a usage like in Figure 2. Nearby the axis of rotation a Heat Exchanger for Low Pressure is situated (HX-LP). In the outer diameter a Heat Exchanger for High Pressure is realized (HX-HP). The thermodynamic cycle starts at point 1.

The whole system rotates around the axis of rotation. The gaseous fluid is ventilated with very slow speed by the fan within the whole system. By compression, point 1 to 2, the temperature is rising from 55°C to 90°C. Because of the very slow speed of ventilation friction losses are very low. This means that exergy losses are rather low causing high efficient compression process.

From Point 2 to 3 the heat release takes place and the fluid is cooled down to 70°C. The heat is removed through a heat exchanger (HX-HP) by a fluid, like water, which basically keeps its temperature even at higher pressures. It enters the rotating system at W3 and leaves it at W4. The temperature is rising from 65°C to 85°C with 5°C Delta between the working medium and the heat transport fluid.

At point 3 the expansion is starting. The temperature is lower and therefore the density at point 3 is higher than before at point 2. Exergy is needed to transport the fluid through the thermodynamic cycle supplied by the fan within the system. This effect is of course well known as the divergence of isobaric curves.

When the fluid has expanded the temperature has cooled down to a lower level at point 4 than on point 1. Because of the very low flow speed the friction losses are rather small again. Heat is needed to close the cycle. It is provided by a fluid entering the system at W1 with 60°C and leaving at W2 with 45°C.

3 PRODUCT AND IMPLEMENTATION

It was shown that the ECOP compression is variable by its nature and high efficient. Indeed compression efficiencies of up to 99.9% can be realized. Through changing the compression ratio the temperature spread between sink and source is impacted by this. The working medium can transfer heat in a broad temperature range, leading together with a variable flow and a variable independent compression ratio to a maximum of flexibility.

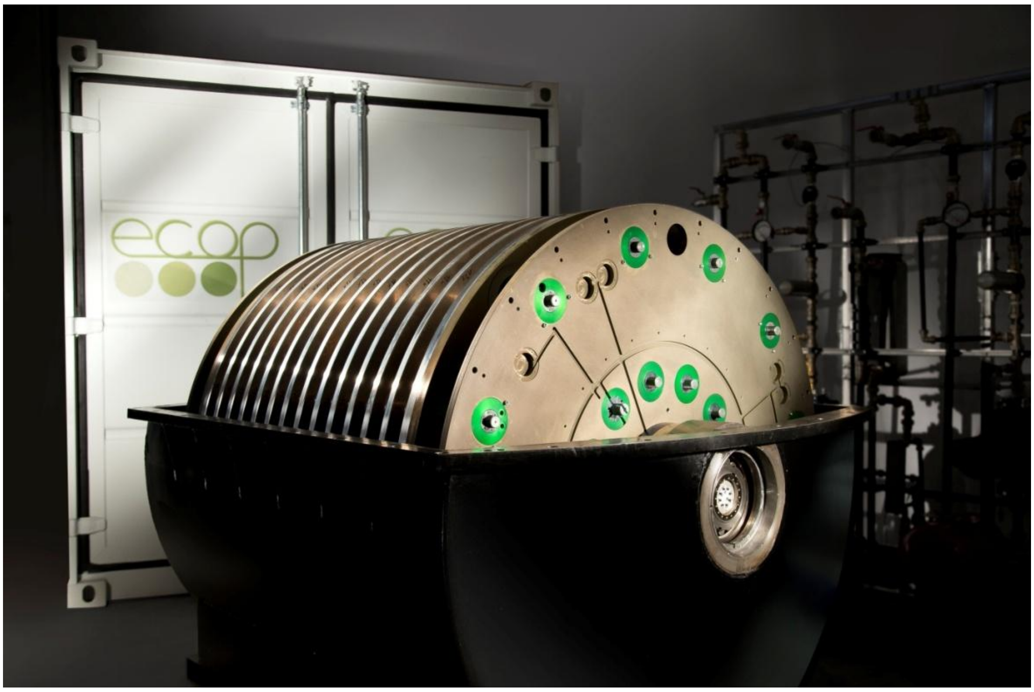

Figure 6: picture of the prototype

The result is a machine that is able to adapt in "real time" to its circumstances, without a change of hardware. Through the usage of sensible heat and the dispension of an isothermal area of the working fluid, the machine can be applied easy and highly efficient for processes which have a higher delta between inlet and outlet, as it is the case for district heating's flow and return.

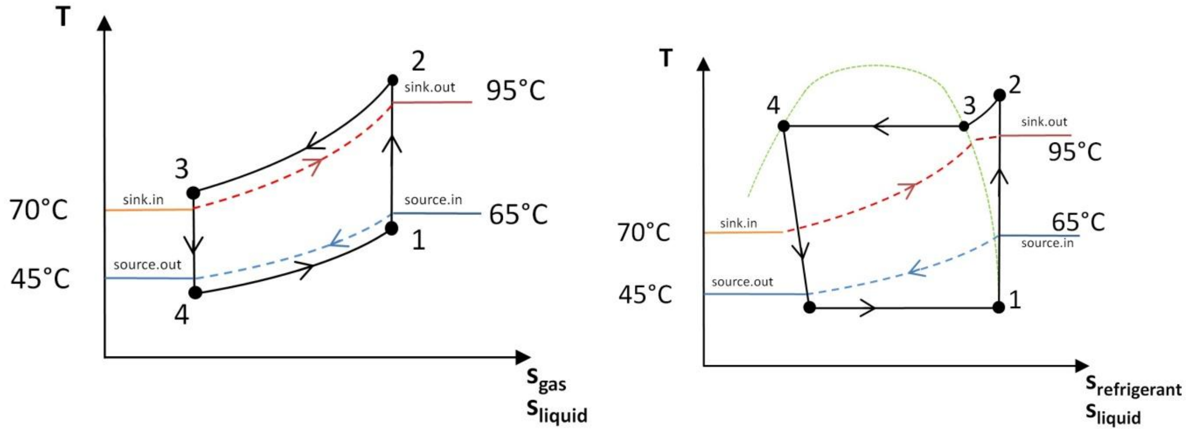

Figure 7: schematic comparison of 1- and 2-phase process

It might be argued that some applications are better off with a 2 phase system realized instead of a one phased, which is for sure right if you have a latent heat for the sink and source too. Yet Figure 7 shows a possibility for the implementation to illustrate the described characteristics. The source is a process stream with 65°C as it could occur when cooling flue gas or other waste heat. The sinks return is 70°C and needs to be heated up to 95°C as it might be the case for a district heating application. It can be seen, according to Figure 1, that rather big exergy losses occur in the heat exchanger for a 2 phase cycle if you realize the application with one stage /machine only.

But what would this mean for a concrete example? Adding a minimum of 3°C Delta for the heat exchanger would lead to the following states for NH3 as the 2 phase medium and Nitrogen as the gaseous working medium.

Table 1: Conditions for the different points in Figure 7 – 2 phase

NH3	Temperature T [K]	Pressure p [MPa]	Entropy s [kJ/(kg K)]	Enthalpy h [kJ/(kg)]
1	318.15	1.7827	5.5736	1634.0
2	410.07	5.4402	5.5736	1795.6
3	366.15	5.4402	5.0572	1596.5
4	366.15	5.4402	2.9365	819.97
5	318.15	1.7827	3.0150	819.97

Table 2: Conditions for the different points in Figure 7 – single phase

N2	Temperature T [K]	Pressure p [MPa]	Entropy s [kJ/(kg K)]	Enthalpy h [kJ/(kg)]
1	335.15	3.8281	5.8602	341.74
2	371.15	5.4402	5.8602	378.90
3	346.15	5.4402	5.7837	351.47
4	312.45	3.8281	5.7837	316.97

Because both systems can be realized in different qualities the ideal COPs (with of course isenthalpic relaxation for the 2 phase system) of those two cycles should be compared.

The two phase cycle can be calculated the following way:

$$COP = (h2 - h4) / (h2 - h1) \quad (2)$$

The resulting COP is 6.0 for NH_3 usage.

For the one phase cycle the operation is similar considering the received energy:

$$Q = h2 - h3 \quad (3)$$

$$W = h2 - h1 - (h3 - h4) \quad (4)$$

$$COP = Q/W \quad (5)$$

$$COP = 27.43\ kJ/kg / 2.66\ kJ/kg \quad (6)$$

The resulting COP is 10.31 for the N_2 usage which corresponds with Carnot efficiency.

This shows that the COP with a one phased cycle, under the given – simplified but similar - circumstances, is nearly doubled.

2.3 Implementation

Basically every process can be realized within a temperature range, mainly limited by materials. Though it is no static rule it was decided to launch products for up to 150°C temperature and machines with capacities of up to 1 MW as a first step for the new heat pump product. Therefore the implementation opens up a broad variety of possibilities. Yet it might be beneficial to focus on implementations which are generating advantages by the possibility of the sensible heat usage for the sink as shown in figure 7. The flexibility of the system is also optimal for applications where source heat is provided on a non constant temperature as it is for most waste heat applications the matter. Beside this the combined solution of cooling and heating is a focus.

2.4 Usage & Status

The design of the heat pump is highly sophisticated making it possible to have a high availability and is made for continuous operation. The characteristics of the machine are maybe more similar to a heat exchanger than to a 2 phase heat pump. While heat exchangers are limited by transferring heat from a higher level to a lower level the ECOP heat pump is not. While realizing further pilot projects, discussions with potential partners are going on regarding distribution and implementation or supporting the supply chain. First interested implementation partners from different industries have already established contact.

4 CONCLUSION

A number of companies developed high temperature heat pumps in order to penetrate the huge industrial market (Wolf 2014). So far diversified refrigerants are used with different characteristics and certain advantages and disadvantages. ECOP is targeting the industrial market, but with a different approach. While the other companies with products for high temperature heat pumps, focus – at least partly - on a two phase approach, ECOP uses a high efficient gaseous cycle with an non toxic, environmental friendly, non flammable working medium, which is found as a component of the air. The technology is offering a maximum of flexibility, a standardized product, able to adapt to its circumstances, in a non standardized industry market. The characteristic of its behavior is pretty simple, comparable to a heat exchanger, making it possible to bring heat to a higher temperature level.

5 CREDITS

This paper gives a short introduction into the ideas and work done so far. Of course ECOP needed financial support to realize what we have done so far and without the help of many different supporters and partners it wouldn't have been possible. Though it is not possible to name everybody since they are too numerous and growing from day to day we would like to mention at least the following.
We would like to express our thanks to "Österreichische Forschungsförderungsgesellschaft FFG" and "ZIT – Die Technologieagentur der Stadt Wien GmbH" for the financial support of this project as well as to Linde AG for our great cooperation.

Thanks and regards to our VC Investors OÖ Hightechfonds and FSP Ventures for believing in the technology and the team as well as the excellent supervision.

Thanks to Professor Ponweiser, Professor Friedl and Professor Willinger, from technical university Vienna, for their great support.

Special thanks to our initial Angel Investor Professor Dr. Michael Mirow, supporting us after his retirement from the SIEMENS Germany advisory board.

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