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Abstract

Heat pumps are among the key technologies for the supply of renewable thermal energy, as well as for the area-wide use of waste heat. They can therefore make an important contribution to the implementation of the EU's climate change targets. In industrial processes, however, these technologies are only occasionally used for heat supply.

This work is intended for the further dissemination of heat pumps in the industry. It is aimed at interested, potential users who would like to bring more renewable process heat into their operations. This work provides guidance on how heat pumps can be integrated into industrial processes and shows which criteria and parameters are important for the identification and evaluation of integration concepts.

First, the technical basics of heat pumps are discussed. The most important technical terms are presented, as well as the state of the art, the possible applications and the limits of the technology. Secondly, the heat pump integration into industrial drying processes is shown.

With 12-25 % of the industrial energy consumption attributable to industrial drying in developed countries, drying and dehydration is one of the most energy intensive and wide-spread processes in a number of industrial sectors which are currently primarily fossil-fired with minimal or no utilisation of waste heat streams. A sucessful heat pump integration into such processes is therefore of major relevance for a number of other, more traditional sectors such as e.g. pulp & paper and petro-chemical industry, which are said to be more reluctant to introduce new, un-proven energy-efficiency technologies.

The gathered information for this work mainly originates from the Austrian research projects *HighRef*, *EnPro SteamUp* and *DryPump* as well as the Norwegian research projects *DryMeat* and *HeatUp*. The ongoing European research project *DryFiciency* brings both drying principles to a demonstration scale on TRL7.

Executive summary

Heat pumps are among the key technologies for the supply of renewable thermal energy, as well as for the area-wide use of waste heat. They can therefore make an important contribution to the implementation of the EU's climate change targets. In industrial processes, however, these technologies are only occasionally used for heat supply.

This work is intended for the further dissemination of heat pumps in the industry. It is aimed at interested, potential users who would like to bring more renewable process heat into their operations. This work provides guidance on how heat pumps can be integrated into industrial processes and shows which criteria and parameters are important for the identification and evaluation of integration concepts.

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1 Introduction

In Europe, electrically driven compression heat pumps are the most widely used and widespread type of heat pumps. Due to its market relevance, this work deals exclusively with this type of heat pumps. The term "heat pump" is used synonymous with electrically driven compression heat pumps.

Heat pumps use heat streams at a low temperature level to provide heat with higher temperatures using electricity. A heat pump system consists of several parts: the heat source system, the heat pump itself and the heat recovery system. The heat source system extracts heat from the heat source and uses a heat transfer medium to transport it to the cold side of the heat pump. The heat pump provides heat at a higher temperature level required for heat utilization by using electricity for the compressor. The heat recovery system (heat sink) transports the heat from the hot side of the heat pump to the consumers.

In buildings, heat pumps are used for heating and hot water production. For example, the ambient air, groundwater or soil serve as heat sources. In industrial processes, waste heat flows are generated which, due to the low temperature level, can no longer be usefully used in the production process or for its supply and are usually released into the environment with additional cooling effort. With the help of a heat pump, these waste heat flows can be raised to a usable temperature level and reintegrated into the production process, see Figure 1.

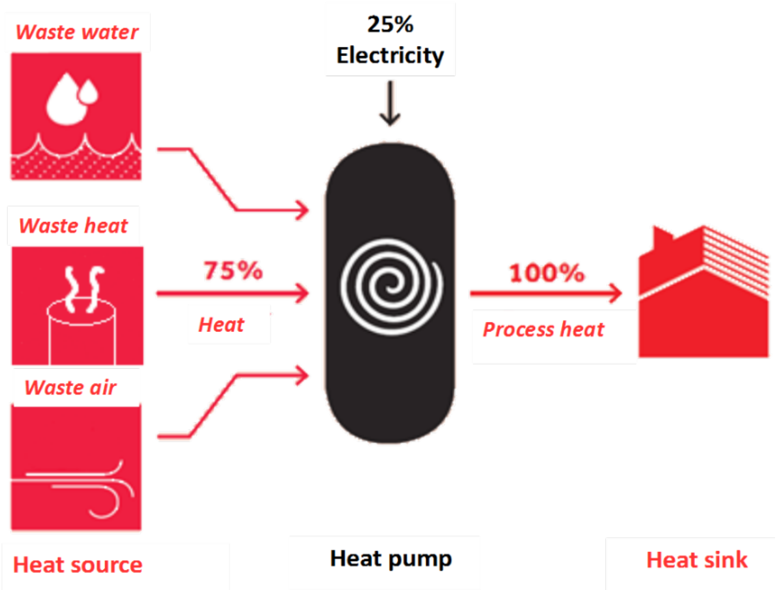

Figure 1: Heat pumps in industry (example figure from [1]).

1.1 Working principle

1.2 Components

The most important components of a heat pump are shown schematically in Figure 2. In the simplest case, a heat pump consists of two heat exchangers - the evaporator and the condenser - a compressor and an expansion valve, and a closed refrigerant circuit. In the evaporator, the refrigerant evaporates at low temperature and low pressure and absorbs energy from the heat source. The compressor compresses the refrigerant vapor and the increase in pressure causes the temperature of the refrigerant to rise. After compression, the refrigerant is available at high temperature and pressure. In the condenser, the refrigerant transfers energy to the heat sink and condenses. The refrigerant is then liquid at high pressure and low temperature. In the expansion valve, the refrigerant is released to the low pressure of the evaporator again.

Speaking in the context of high-temperature heat pumps, the usual component suppliers of commercially available heat pumps have to adapt their products in order to withstand the higher temperature load. For example, the sealings in market available expansion valves are restricted to a maximum temperature of approx. 100°C. In the case of high-temperature applications other sealing materials have to be used.

The state diagram is a pressure enthalpy diagram showing the saturated liquid and vapor of the refrigerant, as well as the heat pump cycle.

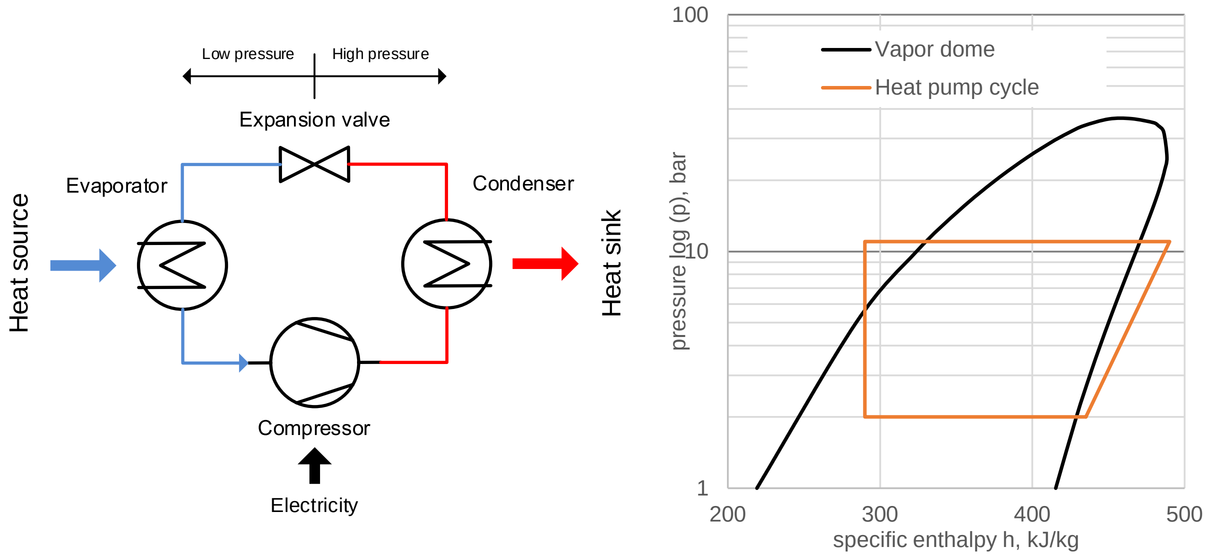

Figure 2: Simple heat pump scheme (left) and state diagram (right) [1].

1.2.1 Evaporator and condenser

These are two heat exchangers that transfer heat from the heat source to the refrigerant and transfer it from the refrigerant to the heat sink. The design of the heat exchangers depends on the requirements of the heat source and heat sink. Plate heat exchangers are usually used for liquid and less polluted media.

1.2.2 Compressor

The compressor transports and compresses the refrigerant. It is driven by an electric motor and, depending on the type, also power control. The following compressors are mainly used in heat pumps:

- Rolling piston compressor
- Scroll compressors
- Reciprocating piston compressor
- Screw compressors
- Turbo compressors

Rolling piston compressors tend to be used in the small capacity range, scroll compressors in the small to medium capacity range and screw compressors in the large capacity range. Turbo compressors cover a wide performance range.

1.2.3 Expansion Valve

The expansion valve (throttle) releases the liquid refrigerant to a lower pressure after heat transfer in the condenser. Normally electronically controlled expansion valves are used.

1.2.4 Refrigerant

The refrigerant is the working medium of the heat pump. The choice of refrigerant depends primarily on the temperature levels of the process. The properties of the refrigerant should be optimally adapted to the process requirements in order to achieve high efficiency. There are numerous requirements for the refrigerant: it must be chemically stable and should have a high volumetric cooling capacity so that the refrigerant charge can be low and the components can be compactly constructed. In addition, the refrigerants should be harmless to the environment and have as little global warming potential (GWP) as possible. When filled with refrigerant as well as when the heat pumps is disposed of, any leakage can cause the refrigerant to be released to the environment, which effects the greenhouse gas effect.

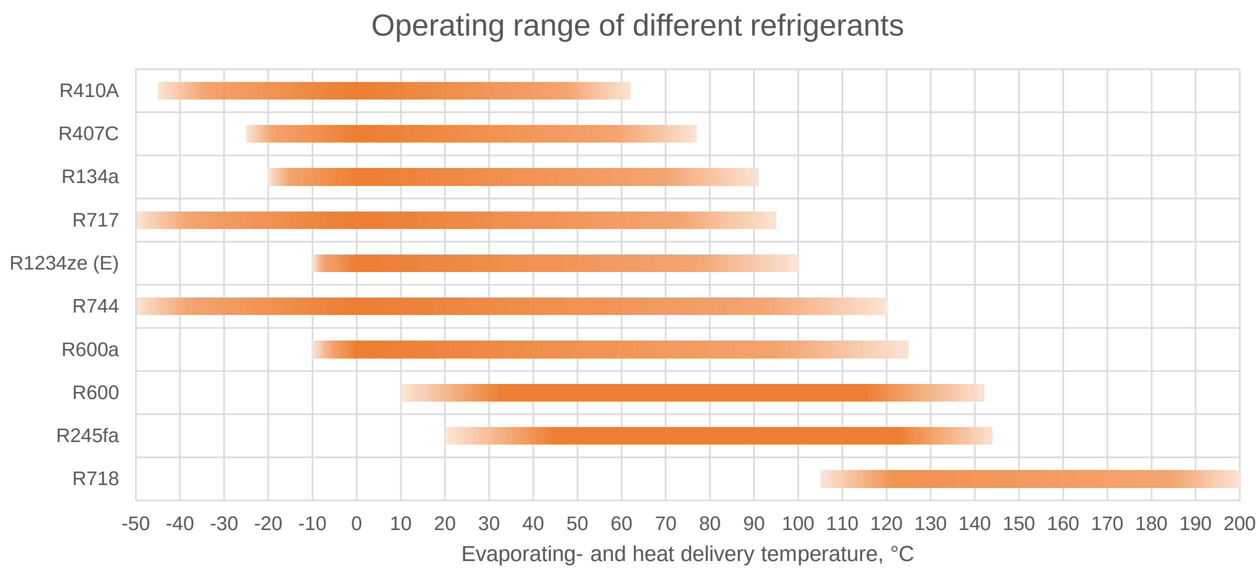

Figure 3: Overview of common refrigerants [1].

Today, hydrofluorocarbons such as Pentafluoropropane R245fa, Tetrafluoroethane R134a and Tetrafluoropropene R1234ze or mixtures of hydrocarbons such as R410a and R407c are typically used as refrigerants. Their global warming potential is comparatively high. Natural refrigerants such as Ammonia R717, Isobutane R600a, n-Butane R600, CO_2 R744 or Water R718 are also used, which have very little or no global warming potential. However, some of them are flammable, toxic or explosive, so special safety regulations must be taken into account. Figure 3 gives an overview of the application range of different refrigerants. The minimum evaporation temperatures and the maximum heat utilization temperatures are shown.

1.2.5 Key figures

The evaluation of heat pumps is based on key figures derived from the energy balance. In the simplest case, the heat output of the heat pump is equal to the sum of the heat extracted from the source and the electrical power of the compressor (without taking losses into account).

The coefficient of performance (COP) is calculated as the ratio of benefit to effort. Accordingly, the COP for heating mode is the ratio of heating capacity to electrical power and describes the efficiency of the heat pump in a particular heating operation point.

$$COP_{\mathrm{Heating}} = \frac{\dot{Q}_{\mathrm{Heating}}}{P_{\mathrm{el}}}$$

The benefit is to be evaluated individually and can be, in addition to the heating capacity, also provided cooling capacity or the sum of heating and cooling capacity.

The annual performance factor or seasonal performance factor (SPF) is the ratio of useful energy to electricity in one year. Therefore, the variable operating points resulting from temperature changes of the source and sink are taken into account in the SPF. The more constant the operation of the heat pump is, the less the SPF differs from the COP. If the heating energy Q_{Heating} is the sole use, the following applies:

$$SPF_{\text{Heating}} = \int \frac{\dot{Q}_{\text{Heating}}}{P_{\text{el}}} = \frac{Q_{\text{Heating}}}{E_{\text{el}}}$$

In summary, the actual value of the key figure for a heat pump integration is always defined as the ratio between benefit and effort. Considering different system boundaries, also additional drive systems (fans, pumps, etc.) can be included.

1.3 Operating strategy

The operating strategy of a high-temperature heat pump in industrial processes distinguishes between two operating states:

- Continuous operation
- Startup phase

The control strategy of a high-temperature heat pump in continuous operation - or even in steady state - does not differ significantly from that of a commercially available heat pumps for space heating or domestic hot water. One then speaks of the basic regulation, which is identical due to the underlying physical laws. Depending on the process requirements and complexity of the application in industrial processes, predictive or model-based control can be used to automatically intervene in the basic control and adapt it to the desired effects. However, the basic rule does not change. The expansion valve regulates to a preset superheat and the capacity of the compressor regulates the flow temperature on the heat sink side. The compressor speed usually controlled by speed control via frequency converter. Partial load control by means of slide controls is a more cost-effective variant, but it cannot be implemented for every type of compressor.

With preset source and sink inlet temperatures and appropriate controller parameterization, constant operation can be achieved without any significant problems. Considering the compressor application limits, such as pressure range, speed range, suction gas or discharge gas temperatures and the correct refrigerant charge, a reliable continuous operation is possible. However, in the case of newly developed refrigerant oil mixtures, the compatibility of the two components with each other and the material compatibility with the sealing components used in the refrigeration circuit must be tested.

Start-up is a critical operating state. A distinction must be made between two cases. It is a big difference whether the source and sink are already close to the operating temperatures during start-up or have to be brought there by the high-temperature heat pump. In the case of pre-conditioned source and sink sides, only the heat exchangers of the evaporator and condenser must be subjected to this pressure before commissioning. After this so-called "passive" start-up phase, the compressor can be put into operation. The basic control described above takes over the operation. The expansion valve immediately opens and regulates to the setpoint of the superheat, which is ensured by a pre-tempered refrigeration circuit.

A hot gas bypass can be provided for "active" start-up with unconditioned source and sink to allow controlled start-up of the cooling circuit. This hot gas bypass also acts as a safety device for dynamic operating conditions. The bypass flap of the hot gas bypass closes at standstill and is not opened again until the refrigerant circuit itself ensures overheating.

A non-return valve upstream of the condenser is provided for both passive and active start-up, so that a back pressure for the compressor is available at start-up and lubrication is guaranteed. The same effect could be achieved if the hot gas is fed directly into the collector vessel during start-up. Adequate lubrication of the compressor right from the start has absolute priority. According to expert talks, insufficient lubrication often results in a total loss of lubrication, which can occur within seconds without a sign and causes inevitable compressor damage.

Depending on the refrigerant, it may also be necessary to temper the housing if the evaporation pressure is lower than the ambient pressure at temperatures below about 30 °C. In this case, air can be sucked in through the negative pressure difference between the ambient and the refrigeration circuit.

2 Drying with High Temperature Heat Pumps

2.1 Motivation

With 12-25 % [2] of the national industrial energy consumption attributable to industrial drying in developed countries, drying and dehydration is one of the most energy intensive and wide-spread processes in a number of industrial sectors which are currently primarily fossil-fired with minimal or no utilisation of waste heat streams, see Figure 4. A successful heat pump integration into such processes is therefore of major relevance for a number of other, more traditional sectors such as e.g. pulp & paper and petro-chemical industry, which are said to be more reluctant to introduce new, un-proven energy-efficiency technologies [3].

The two most important drying concepts found in processing industries are convective drying using either air or steam as a drying agent. For some years now, work has been underway on the development of high-temperature heat pumps with heat recovery temperatures of up to 160 °C in order to power such drying systems. These high temperatures are already possible in experimental heat pump systems and it can be assumed that such systems will become marketable in the next few years.

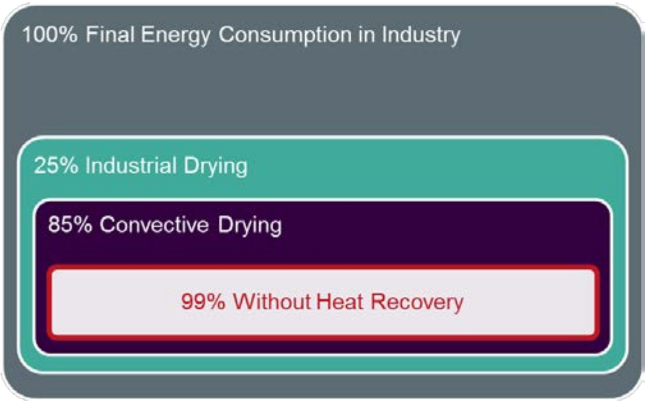

Figure 4: Energy consumption in industry, adapted from [4].

Preliminary work at the research organizations AIT and SINTEF ranging from Technology Readiness Level (TRL) 1 to TRL 5 represents the joint efforts so far in order to push the high temperature heat pump development on component level but also identify suitable industrial processes. The conceptual projects *BrickDrying* and *EnPro* at TRL 1 showed the high potential of heat pump systems for industrial drying processes leading to the essential conclusion that temperatures from 100 °C to 180 °C are needed to take advantage of the full technical potential of waste heat recovery in drying and dehydration processes, and thus significantly reduce CO_2 emissions and product costs. The follow–up projects *DryMeat* and *HighRef* focused on experimental work at TRL 3 on novel heat pump systems in lab scale applications with supply temperatures of up to 160 °C (closed loop in *HighRef* [5]) and 180 °C (open loop in *DryMeat*). The projects identified a means to recover low-grade drying energy and upgrade by the use of heat pumps to power the drying process by its own waste energy and thereby reduce the energy demand by up to 80 %. The projects *HeatUp* and *DryPump* at TRL 4 resulted already in technical concepts for heat pump integration for the industrial processes. *HeatUp* identified also the potential of novel turbo-compressor technology in steam compression cycles including a lubrication-free system design.

2.2 Drying

Drying is one of the oldest preservation technologies and made it possible for humans to store food for extended periods of time. Thus drying has been a crucial technology in the evolution of human cultures. To this day drying is still one of the dominating industrial preservation processes for innumerable products. Industrialization helped to optimize processes of drying, which are conducted under varying, but controlled conditions.

In drying technology, the term convective drying is used to indicate when heat and mass transfer are due to the temperature and pressure gradients, respectively, between the drying agent (DA) and the drying product. The purpose of the drying agent in convective drying is to supply the necessary energy for the evaporation of the moisture from the product, capture the evaporated water and remove it from the drying system. The speed at which the moisture is removed is commonly referred to as the drying rate.

Figure 5 (left) shows a conventional open-loop drying process with 100 % heat input, which is usually fossil fired. The amount of unused surplus heat incl. evaporated water is approx. 80 %. The state graph at the bottom gives an overview of the drying process in the Mollier-diagram. The drying agent is heated up from point 1 to point 2 and takes up the moisture from the product to be dried (point 2 to point 3). A heat pump integration allows to recover over 90 % of the heat input. Figure 5 (right) shows the closed-loop drying system with integrated heat pump.

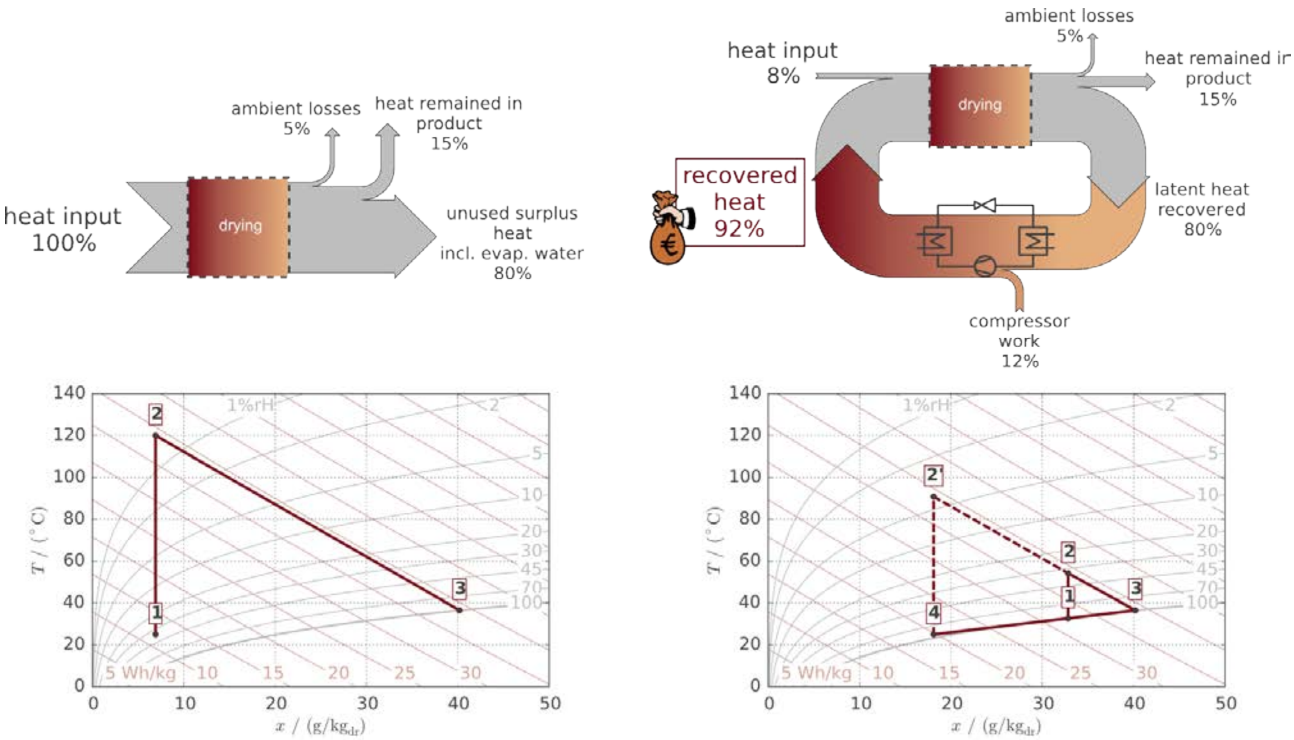

Figure 5: Motivation for integrating heat pumps into drying processes.

2.3 DryFiciency

The recent research activities led to the H2020 European research project *DryFiciency*, where SINTEF and AIT collaborate in order to demonstrate the feasibility of high temperature heat pumps for drying processes at

TRL7. Three different industrial drying processes are considered in the project. These are applications and development of thermal drying in the agricultural raw material industry, in the ceramic industry, and in the pet care/feed industry. In the agricultural raw material application, the heat pump technology will be developed for the production and drying of starch from potatoes, wheat and corn. The demonstration of this heat pump system will take place at Agrana Stärke GmbH in Pischelsdorf, Austria. For the application in the ceramic sector, the focus is to integrate novel heat pump technology for green brick drying. This technology will be implemented by Wienerberger AG in Uttendorf, Austria. Finally, the application for the pet food/feed industry focuses on the production and drying of kibble or dried fodder. This heat pump drying system will be developed and installed by Mars Petcare GmbH in Verden, Germany.

To utilize the waste heat streams of the above drying processes, two advanced high temperature heat pump systems will be developed. The first system is a closed loop cycle based on the low global warming potential (GWP) refrigerant HFO-1336mzz-Z with beneficial thermodynamic properties at the identified drying temperatures. Thus, the closed loop heat pump system is suitable for supply temperatures up to 160°C . The closed loop cycle is for convective air drying and will be integrated into the dryers for starch (Agrana Stärke) and bricks (Wienerberger). The second heat pump system is an open loop cycle where water (R718) is the refrigerant. Such systems are commonly referred to as MVR (Mechanical Vapour Re-compression). In this system, the heat pump cycle directly utilizes the excess steam from the drying. The open loop cycle for convective superheated steam drying will be integrated into dryers for kibble (Mars Petcare).

The goal of the integration of the novel high-temperature heat pump systems in the above described industrial drying processes is to recover the waste heat streams so that the specific energy demand is reduced by as much as 60-80%.

2.4 Convective brick drying with air as drying agent

Industrial brick drying is typically performed in convective dryers using hot air from the kiln as well as fossil fuel burners. The freshly shaped green bricks with a moisture content referred to the dry mass of approx. 30 wt% are dried to the maximum allowed kiln-entrance humidity of 1 to 4 wt% in an open-loop drying system as shown in Figure 6. Open-loop dryers operate using hot supply air as a heat carrier whereas the humid exhaust air is released to the environment energetically unused. According to [6] 85% of drying operations are performed in fossil fuelled convective dryers, of which 99% operate as open-loop systems.

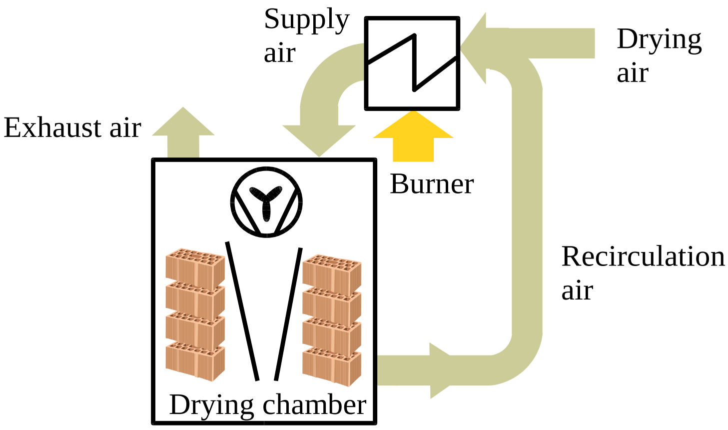

Figure 6: Schematic diagram of the conventional open-loop process of brick drying.

The necessary heat for evaporation of the moisture in the drying product can be supplied by a heat pump, which delivers thermal energy from a heat source to a heat sink at higher temperature. In case of a mechanical vapour compression heat pump additional electric energy is supplied to the compressor. The principle can be used in open-loop drying systems, by heating the supply air to the drying temperature using a heat pump and an external or internal heat source. Another possibility is heat pump drying in a closed-loop cycle as illustrated in Figure 7. The HP recovers sensible and latent heat by cooling and condensing moisture from the humid exhaust air of the drying chamber. The dehumidified air is subsequently supplied back to the dryer after reheating by the HP. The closed-loop system allows to control the temperature, humidity and airflow rate of the drying air accurately and independently, therefore accelerating the drying cycles and preserving the quality of heat sensitive product. Moreover, using heat pumps substantially reduces the overall energy consumption of the drying process by up to 80% [7].

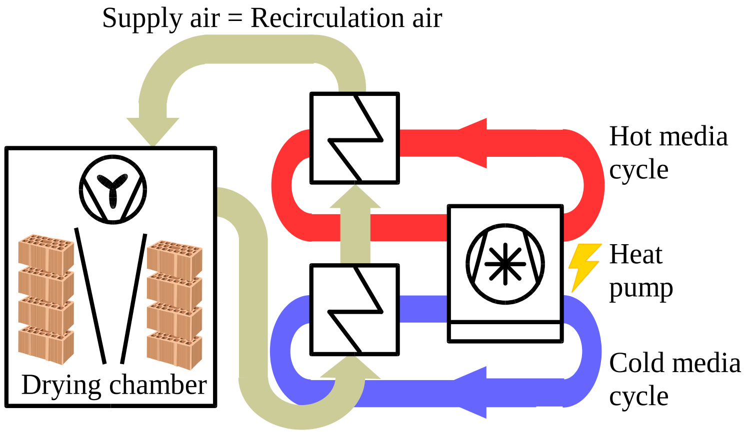

Figure 7: Schematic diagram of closed-loop heat pump drying of bricks.

However, chamber dryers operate under fluctuating production capacities, and hence allow for some degree of flexibility in drying time and drying temperature. Since the efficiency of the heat pump depends on the temperature lift between evaporator (heat source) and condenser (heat sink), lower drying temperatures may increase the efficiency of the overall heat pump drying process. To evaluate and optimize the drying conditions as well as the overall process efficiency, experiments were performed on a small-scale laboratory chamber dryer retrofitted with a heat pump cycle.

The experimentally determined values of the specific energy consumption (SEC) are in good accordance with data measured in heat pump dryers for timber [8] and considerably lower than for most industrial dryers, which typically have SEC values of over 1 kWh/kg [9]. However, while the final moisture content of timber is approx. 10 to 20 wt%, bricks require a maximum humidity of 1 to 4 wt% to avoid crack formation in the kiln. On the one hand bricks are difficult to dry with convective dryers due to the poor heat transfer characteristics particularly when the growing dry surface layer increases heat and mass transfer resistance. To overcome the reduced drying rate, higher drying temperatures are necessary in the end of the drying process.

To test the drying process at moderate temperatures, the drying container was equipped with a closed-loop air circulation cycle and a commercially available heat pump. Hence the maximum heat sink temperature of the installed heat pump is approx. 90°C. Furthermore, the container loses a significant amount of heat due to lack of heat insulation and air leaks. However, since the test series was conducted in summer at high ambient temperatures the heat losses owing to wall conduction are assumed to be relatively minor. The majority of energy losses is attributed to air leaks in the drying chamber. Comparing the condensate mass stream from the dehumidifier to the mass loss of the bricks, the humid-air leak contributes between 20 to 35 wt% of the total moisture removed from the drying product. Moreover, ambient air dilutes the air in the drying chamber, reducing the relative humidity and thus the dew point of the exhaust air. This lowers the temperature in the dehumidifier and increases the temperature lift of the heat pump required to heat the supply air to the specified temperature. Therefore, it is essential to minimize air leakage to ensure optimized process operation.

In general the average COP of a heat pump used for drying should be higher than 4 to operate efficiently and economically [8]. Since the heat pump operated with a COP between 2 and 3.5 during the experimental drying cycles, there is some room for improvement. To lower the temperature lift and hence improve the

COP, the two intermediate circuit, which connect the heat pump cycle and the drying cycle, may be omitted. If the dehumidifier and heat exchanger are built as a module and the refrigerant flows through the dehumidifier and the two heating register, the thermal energy is used directly. However, the heat supplied by the heat pump can be distributed with more flexibility and thus more efficiently if the heat pump cycle is connected with the dryer by means of intermediate cycles.

To reach the maximum allowed kiln-entrance humidity and increase drying speed and thus productivity, the bricks must be dried using a higher drying temperatures, at least for a part of the drying process. In recent years high temperature heat pumps with heat sink temperatures of up to 180°C were developed and their viability was experimentally proven [10, 11]. The functionality of HTHP will be demonstrated in a follow-up project, which includes the implementation into a commercial large-scale chamber dryer for bricks.

2.5 Convective drying with steam as drying agent

Convective drying can also be performed with superheated steam as drying agent. As outlined in the HighEFF memo "Energy efficient drying systems: Evaluation of future trends and possibilities" (Deliverable D3.2_2017.03 superheated steam is in many ways a better drying agent than air due to its physical properties, heat and mass transfer, as well as more efficient penetrability. The heat transfer coefficient of steam is twice of that of air. The viscosity (penetrability) of steam is at the same time almost half of the viscosity of air. Superheated steam drying therefore has the potential to shorten drying time and energy demand by 20-30% compared to air drying. However, the most important advantage with respect to energy efficiency is the possibility to implement so called Mechanical Vapour Recompression (MVR)

Mechanical Vapour Recompression (MVR) is a special heat pump application in which steam (R718) is used as refrigerant. The evaporation of the refrigerant unlike conventional heat pumps not done in a heat exchanger; instead the refrigerant is evaporated by the primary process, e.g. distillation or drying. In the literature MVR is sometimes referred to as open loop or open heat pump. One obvious advantage is that the main thermal process can act as an evaporator for the heat pump, which reduces the amount of needed components (= investment costs) and the heat transfer losses (= increased system efficiency).

In the *DryFiciency* project a demonstration unit for MVR-SHS-drying will be implemented on an industrial pet-food dryer. In the superheated steam drying process with MVR at Mars Petcare, an open loop heat pump replaces the electrical or gas driven heater. Figure 8 shows a schematic diagram of the modified drying process, where the MVR utilizes the latent heat of the surplus steam from the dryer. As the superheated steam exits the dryer at a temperature of 110ºC, excess steam formed due to the evaporation of moisture during the drying process, is diverted to the compressor and thus becomes the working fluid of the heat pump. The remainder of the steam is recirculated back in the system by a fan, i.e., the heat exchanger reheats the main steam flow before being sent back to the dryer.

Due to its thermodynamic properties, water vapour has proven to be an efficient working fluid for heat pumps with a condensing temperature above 100ºC. In the national project *HeatUp* (NFR-grant 243679) turbo-compressors were identified as the most promising energy- and cost efficient compression technology for this process. In Work Package 2 of the project, an efficient turbo-compressor will be tailor-designed to the boundary conditions of the superheated steam dryer and utilize steam as the working fluid. The turbo-compressor can be designed for a maximum pressure ratio of 2.5 for the steam, which is equivalent to a temperature lift of approximately 25ºC. For the Mars Petcare drying process, it is desirable to increase the steam temperature from 110ºC to temperatures in the range 155±5ºC. Thus, a two-stage compressor is required in order to accomplish the required temperature lift.

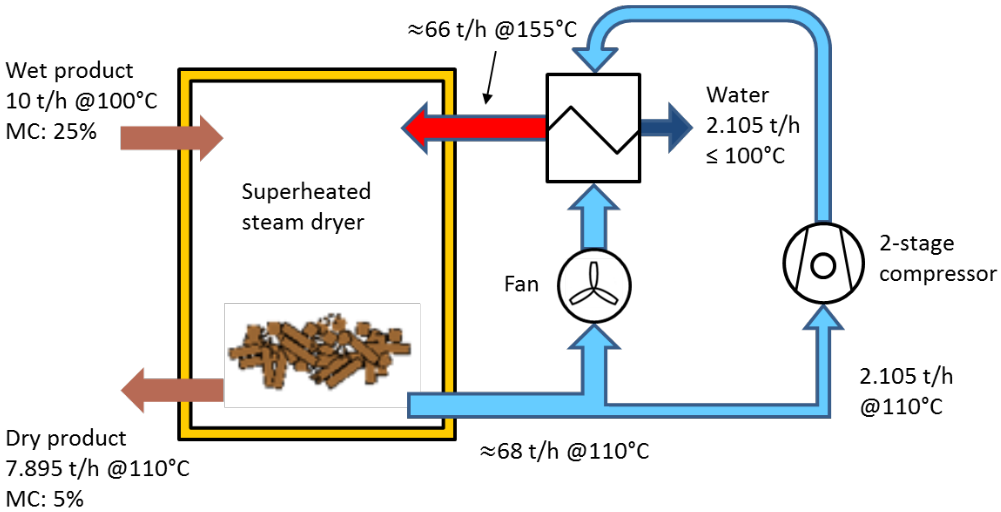

Figure 8: Schematic diagram of heat pump superheated steam dryer for pet food drying. The excess steam is compressed to high pressure and temperature by a two-stage compressor. The latent heat is used to superheat the recycled steam flow for the dryer from 110ºC to 155ºC.

2.6 Other drying processes

Due to high temperature heat pumps, which are in development and allow operating temperatures of around 160 °C, the application fields of heat pump drying can be extended to numerous other drying processes, such as the paper, pulp, petrochemical and non-metallic mineral industries, as well as in the food industry. Figure 9 shows an overview of the drying agent temperatures required for drying of various food products, which are usually between 100°C and 200°C.

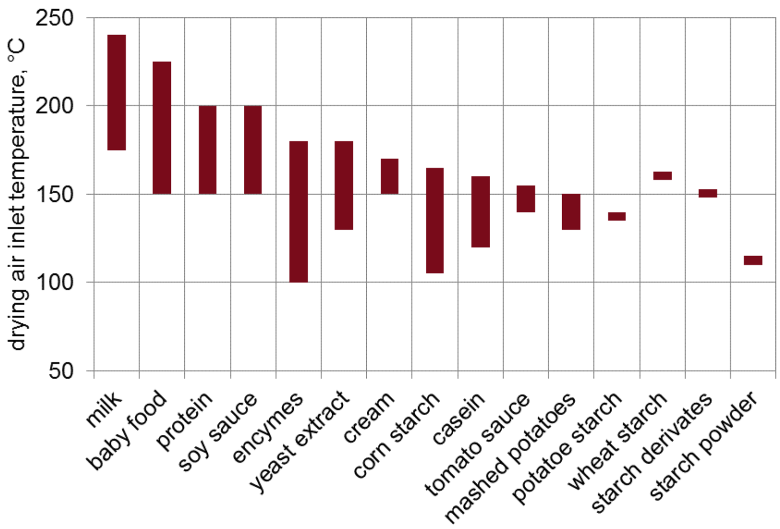

Figure 9: Overview of temperature demand for different drying processes in the food sector.

3 Market available high temperature heat pumps

Despite the huge potential, there are commercial barriers to the spread of high temperature heat pumps. Among other things, it is the scepticism due to a lack of knowledge and experience with heat pumps, the availability of competing technologies for generating high temperatures, the low energy prices for fossil fuels, the lack of availability of refrigerants with low global warming potential and, in particular, the still too low achievable temperature levels. The range of heat pumps on the market with high output and high flow temperatures has grown steadily over the past few years. A literature study [12] has identified 19 heat pumps from 12 manufacturers (Kobe Steel, Hybrid Energy, Mayekawa, Dür Thermea, Ochsner, Combitherm, Friotherm, Star Refrigeration, GEA Refrigeration, Johnson Controls, Mitsubishi, Viessmann) which supply at least a flow temperature of 90°C. The heat pumps are available in different sizes.

Figure 10 shows these industrial high temperature heat pumps available on the market, sorted according to their maximum delivery temperature and heating capacity (logarithmically plotted). Most high temperature heat pumps reach flow temperatures from 90°C to 95°C. The Kobelco SGH 120 compression heat pump and the Mayekawa Eco Sirocco heat pump hot air heater (with supercritical CO2) set the industrial benchmark at 120°C. Kobelco SGH 165 (white bar) is a heat pump steam generator that generates 120°C of steam through a heat pump and compresses the steam to 165°C via a vapour compressor. The Hybrid Heat Pump from Hybrid Energy AS works according to the absorption principle (grey bar).

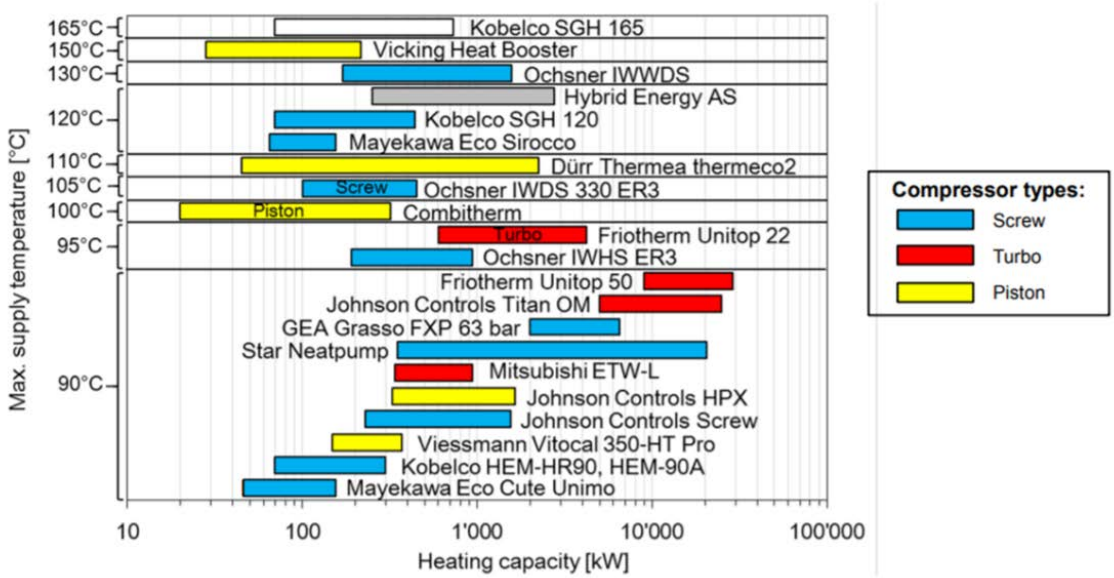

Figure 10: Available high temperature heat pumps [12].

Originating from the development in the Organic Rankine Cycle (ORC) technology, Viking Heat Engines have a market available heat pump – the Viking Heat Booster – which can produce heat up to 160 °C from waste heat and other low temperature heat sources. The ORC is similar to a steam engine process, but uses organic fluids instead of water. These fluids have lower boiling points and other positive attributes that make them more suitable for low-temperature operations. Viking Heat Engines deliver complete heat pump packages or compressors only.

A number of organic working fluids have been selected for the piston compressor, whose saturation curves determine the temperature boundaries of the system. For the HeatBooster, the current working fluids can be divided into a temperature range from 70-140°C and from 90-165°C, respectively. HFC-245fa covers the lower temperature range and HFO-1336mzz(Z) (Opteon MZ) covers the higher temperature range.

4 Research on high temperature heat pumps for 200°C sink temperature with water as refrigerant

Appropriate heat pump technology is important for reducing CO_2 emissions and primary energy consumption as well as increasing amount of renewable energy usage in industrial processes. The expansion of industrial applications is also important for enhancing these effects further more. In particular, development and dissemination of high-temperature heat pumps for hot water supply, heating of circulating hot water, and generation of hot air and steam are necessary. Specific problem areas are

- lack of refrigerants in the interesting temperature range
- lack of experimental and demonstration plants

The research activities in the past years are summarized in [13]. For an overview of actual research activities, [12] gives a good and comprehensive overview for high temperature heat pumps. In order to provide heat in the range of 200°C, the availability of useful refrigerants is restricted. As shown in Figure 3, R718 or water is a proper candidate, which can be operated economically in this temperature range.

Water as a natural refrigerant is completely harmless to humans and animals (greenhouse potential GWP=0, ozone depletion potential ODP=0, non-toxic, non-flammable, non-explosive). In addition, the natural and synthetic refrigerants known today are not well suited for use at temperatures of 150 and 200 °C, as the cycle process would then have to be supercritical. The supercritical cycle of the heat pump with carbon dioxide as a refrigerant is well known, but it is only used to a limited extent because the user fluid has to undergo very large temperature differences in the supercritical range in order to be operated economically, i.e. sink-side inlet temperature of 30°C and outlet temperature of 90°C. A refrigerant with a critical temperature higher than the required sink temperature is ought to be selected.

When water is used as a refrigerant in high-temperature heat pumps, the following technical problems arise:

- high compressor discharge temperatures and thus extreme stressing of the components' materials used in the compressor
- high pressure ratios
- high required flow rates due to the low volumetric cooling capacity of water

On the contrary, when water is used as a refrigerant, there would be the possibility that directly processed process feed water could evaporate and be compressed and used directly as process steam when it is integrated into the process steam supply (e. g. in the food and paper industry). As a result, the condenser is no longer needed and investments in the heat pump system would be significantly reduced.

4.1 Closed loop heat pumps with piston compressors

Within the Austrian research project *SteamUp* the usability of water as refrigerant in high temperature heat pumps for condensing temperatures up to 200°C was investigated in order to make use of the idle industrial low temperature (60 to 90°C) waste heat potential. As the compressor is playing a key role, the focus lied on the development of a new compressor concept for the use in industrial processes.

It has also been found that the compression of water vapour in a reciprocating compressor, as part of a compression heat pump, is feasible. The high thermal load can be reduced by direct injection into the cylinder chamber. In this case, the temperatures would then be within a normal range and longer operating times for the packs and rings could be guaranteed. The question of the efficiency of the heat pump, or rather the willingness of companies to invest in such a system, remains unresolved at this point.

The realisation of a high temperature heat pump with a piston compressor and water as refrigerant is theoretically possible. Whether a 2 or 3 stage system is going to be implemented, depends on the exact application and on the temperatures required in the respective process.

The approach with direct injection of water into the compression stroke of a three-stage piston compressor was selected as the best variant. Figure 11 (left) shows an exemplary cycle for an evaporator temperature of 80 °C and a condensation temperature of 200 °C, the target maximum. By direct injection, the final compressor temperature of approx. 660 °C for the single-stage process, or approx. 390 °C for the two-stage process with intermediate injection, can be reduced to the condensation temperature of 200 °C. Figure 11 (rigth) shows a possible conifguration of a high temperature heat pump with piston compressors and water as refrigerant.

To cool the condensed water vapour, finely atomised water is injected into the cylinder. The atomisation is intended to produce a relatively large surface area of the droplets in order to enable rapid evaporation.

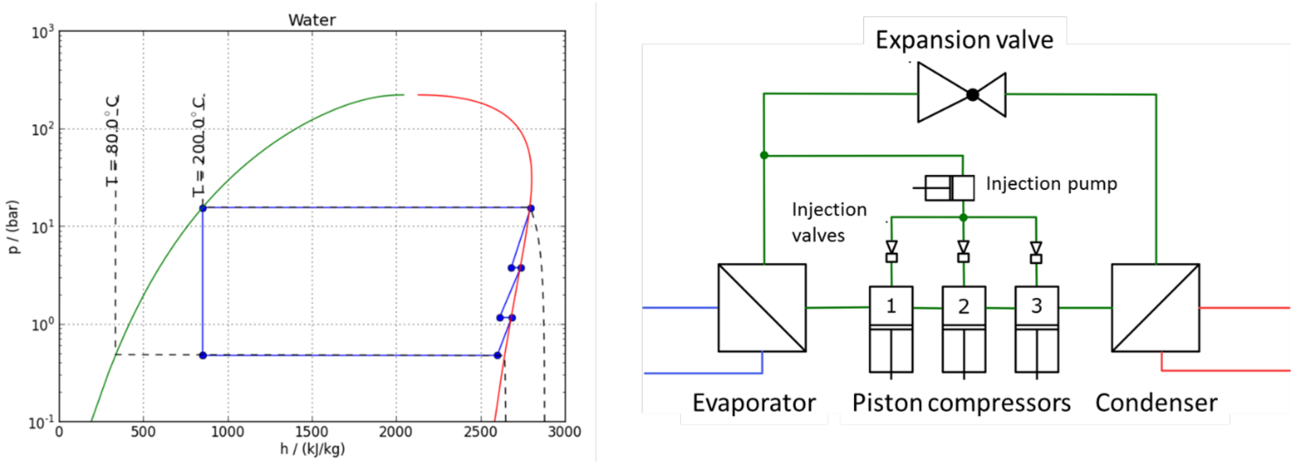

Figure 11: Heat pump cylce with direct injection (left) and scheme of the piston compressor configuration (right).

4.2 Open loop MVR with turbo compressors

Mechanical Vapor Recompression (MVR) systems are open loop heat pump systems designed for R718 (water) and are implemented in thermal processes where steam is used as (sensible) heat carrier, while the core process is delivering excess steam. This is the case for processes like evaporators, boilers, dehydration and drying applications. The core process is functioning as the evaporator of the MVR-heat pump (hence open cycle) and the transferred energy in the condenser is used to re-heat the heat carrier (equals supply steam). The temperature lift between excess and supply steam is defining the required pressure ratio of the MVR-system. MVR is presently used to some extend in industrial processes, e.g. breweries, paper industry, petrochemical industries and refineries. MVR cannot be applied if the surplus heat is a condensate or if the excess steam is too contaminated (e.g. with particles).

Compression technology for steam/water-vapour is the key element for MVR or steam based heat pump cycles. Only a few suppliers can offer suitable compressors or complete plants. However, the thermal capacity of the system should have a minimum of 5 MW when a temperature lift of 50 Kelvin is required. This is due to the high thermal energy in steam condensation, the (fixed) volume of the compressor and the significant volume reduction of steam during compression (especially important for multistage compression). For smaller temperature lifts (maximum of 10 Kelvin) steam fans or (roots-) blower can be applied. They are relatively cheap and already implemented in the industry. Investment costs for compressor based MVR will be quite high (around € 1 million per MW), since the compressors will be tailor-designed for each application. In principal blowers or fans would be more economic to install, but they also require several compression stages (5 or more stages for 50 Kelvin temperature lift). It is unclear how this complexity will affect investment costs, but also stability.

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MVR compression technology is currently limited to small temperature lifts (lower than 20 Kelvin), which give a minor increase in process efficiency, but can be achieved with reasonably priced compression technology (fan/blower). Larger temperature lifts (larger than 30-40 Kelvin), which are required in order to achieve high process efficiencies, are only reached with expensive tailor designed compressors. For both cases the ROI (return of investment) is normally several years, depending on local energy prices.

For thermal systems in the capacity range of 0.5 to 4 MW no suitable compressor technology is available which can give temperature lifts larger than 30-40 Kelvin. Turbo-compressors were identified by the *HeatUp* project as a suitable technology to reach high temperature lifts (up to 80 Kelvin) for relatively small thermal capacities (1.2 MW).

Figure 12: Compact Turbo-Compressor with lubricated planetary gearbox, up to 100 000 rpm, 200 $kW_{thermal}$, impeller diameter smaller 100mm.

4.3 Other technologies

Research activities at the Energy research Centre of the Netherlands (ECN) are focussing on the so called Thermo acoustic heat transformer. Thermo acoustic (TA) energy conversion can be used to convert heat to acoustic power (engine) and to use acoustic power to pump heat to higher temperature levels (heat pump). The systems use an environmentally friendly working medium (noble gas) in a Stirling-like cycle, and contain no moving parts.

Although the dynamics and working principles of TA systems are quite complex and involve many disciplines such as acoustics, thermodynamics, fluid dynamics, heat transfer, structural mechanics, and electrical machines, the practical implementation is relatively simple. This offers great advantages with respect to the economic feasibility of this technology. When thermal energy is converted into acoustic energy, this is referred to as a Thermo acoustic (TA)-engine. In a TA-heat pump, the thermodynamic cycle is run in the re-verse way and heat is pumped from a low-temperature level to a high-temperature level by the acoustic power. This principle can be used to create a heat transformer, as shown in Figure 13 below.

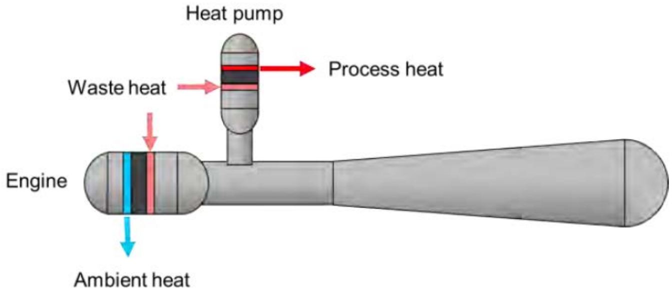

Figure 13: Principle of the thermo acoustic heat transformer [13].

The TA-engine is located at the left side and generates acoustic power from a stream of waste heat stream at a temperature of 140°C. The acoustic power flows through the resonator to the TA-heat pump, located on top of the resonator. Waste heat of 140°C is upgraded to 180°C in this component. The total system can be generally applied into the existing utility system at an industrial site.

5 Summary and Conclusion

In this work the technical basics of heat pumps have been discussed. The most important technical terms were presented, as well as the state of the art, the possible applications and the limits of the technology.

Market available heat pumps can deliver heat up to 160°C. In order to reach higher temperatures, refrigerants with a critical temperature higher than the required sink temperature are ought to be selected. In this temperature range R718 or water is a suitable candidate to reach temperatures in the range of 200°C. In the case of steam-generating heat pumps, the open loop systems are more efficient than the closed loop systems, because the intermediate circuit of heat delivery is no longer required and steam with a higher temperature can be supplied with the same compression. The compressor as key element in the refrigeration circuit plays an important role in terms of investment costs.

In the European research project *DryFiciency*, the project consortium aims to develop three prototype heat pump installations for industrial waste heat recovery from drying processes and its demonstration on-site. In all three cases the sensible and particularly latent heat of the drying agent is used as drying energy and can be recovered by closed or open loop heat pump systems. A successful heat pump integration into the industrial drying sector has also of major relevance for a number of other, more traditional sectors such as e.g. pulp & paper and petro-chemical industry, which are said to be more reluctant to introduce new, un-proven energy-efficiency technologies.

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