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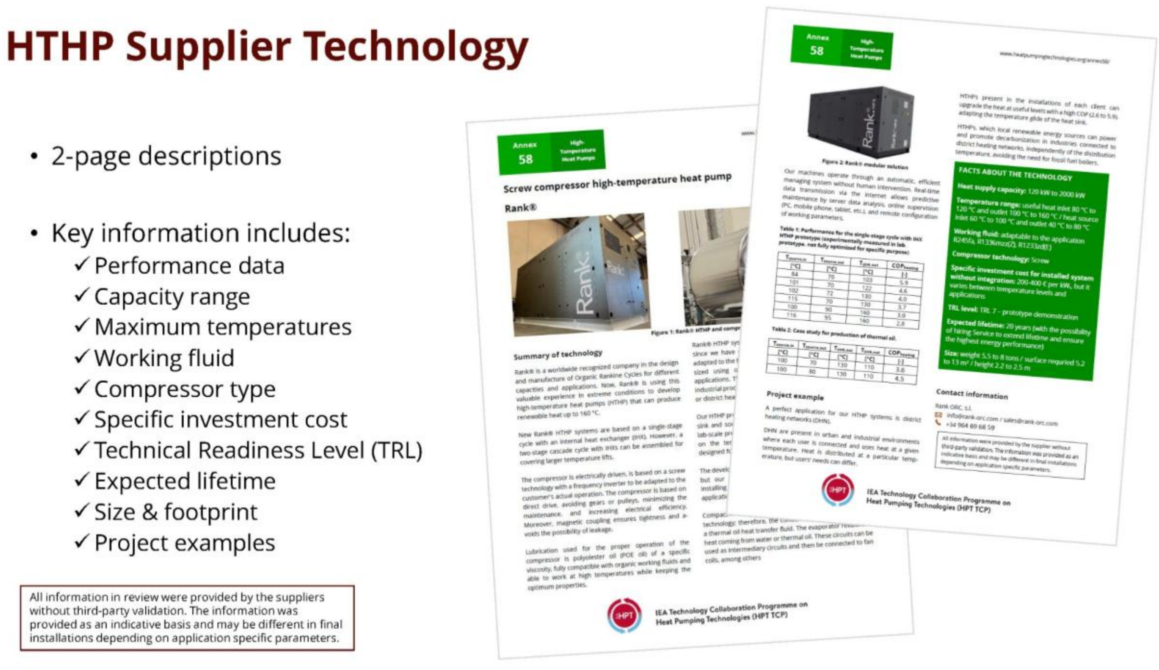
Final report from 12 October 2022

Annex 58 HTHP-CH – Integration of HTHPs in Swiss Industrial Processes

Appendix 2

Factsheets HTHP Technologies



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This is an appendix to the summary report on the project "Annex 58 HTHP-CH – Integration of HTHPs in Swiss Industrial Processes". The report and other appendices can be downloaded at https://www.aramis.admin.ch/Texte/?ProjectID=49514.

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High-Temperature Heat Pump Technologies
IEA HPT Annex 58

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Data source: IEA HPT Annex 58
Website: https://heatpumpingtechnologies.org/annex58/task1/
Summarized by the Swiss team of Annex 58 HTHP-CH
12 October 2022

Rotation Heat Pump

ecop Technologies GmbH

Figure 1: Rotation Heat Pump – RHP K7.

Summary of technology

The Rotation Heat Pump is based on the Joule-Cycle realized in a closed pipe system and allows energy-efficient heating and cooling in industrial applications as well as in district heating system. The integrated regulation enables a wide variety of application cases. Those are for example

- Pulp and Paper industries,
- Food & Beverage
- Chemical Industry
- District heating applications
- Drying (bricks, wood, etc.)
- Pasteurization
- Distillation

Since the compression of the environmentally friendly refrigerant is achieved by centrifugal forces it is very efficient and not depending on special lubrication. The working fluid, consisting of Helium, Argon and Krypton, is not flammable and not toxic while the Global Warming Potential (GWP) is zero. Further, the working fluid is always gaseous and not condensing and evaporating in the heat exchangers. This allows higher temperature spread of sink and source, the heat transfer is sensible. Another important advantage is the flexibility in terms of the temperature level. The Joule cycle allows to switch between different temperature levels always having a high efficiency.

The regulation in temperature lift is realized by a change in rotational speed. For an energy-efficient and flexible operation the machine is driven by frequency converter controlled electric motors.

One demonstration plant of the type RHP K7 is already installed in Austria close to Vienna. This implementation uses waste heat of a steam turbine where the heat was previously dissipated via fans. The Rotation Heat Pump lifts this low temperature heat to temperatures of the district heating system. Due to the flexibility daily and seasonal variations can be covered easily. A further plant is already finally assembled and tested at the company's site where also continuous improvements are done. Also, this RHP K7 will be implemented as a demonstration plant in a good fitting case. The nominal thermal power of each machines is defined as 700kW at the sink. Figure 1 shows a Rotation Heat Pump where the housing is raised and the rotor is clearly visible.

Table 1: Performance.

$T_{source,in}$ [°C]	$T_{source,out}$ [°C]	$T_{sink,in}$ [°C]	$T_{sink,out}$ [°C]	$COP_{heating}$ [-]
120	102	120	150	5.8
90	58	95	130	4.5
85	67	90	120	5.0
50	33	70	90	4.4

Brick drying process (not realized yet)

The drying of bricks requires an enormous amount of heat. The humid air with a temperature of approx. 40°C, which is generated during this process, is usually not further used or utilized in this form because the temperature level is too low. By using a heat pump in combination with a condensation heat exchanger, this residual energy, which is in the range of several MW, can be recuperated back into the cycle. Due to shift operation or fluctuating temperatures, conventional heat pumps are usually not optimally suited for these drying processes.

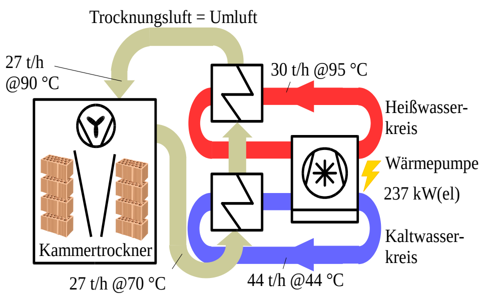

Figure 2: Brick drying process, Source: AIT, DKV-2016, Kassel.

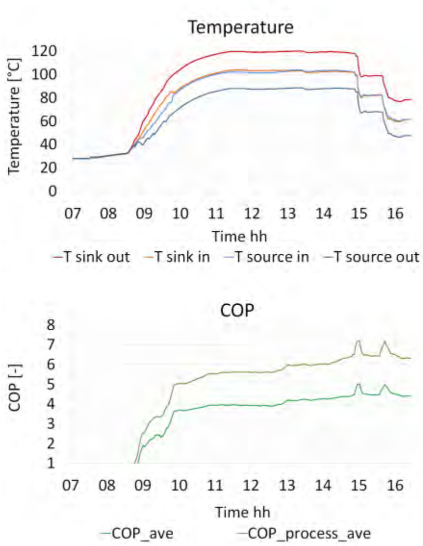

Figure 3: Example for flexible Temperature levels at almost constant COP based on test results of an RHP K7.

Figure 2 and Figure 3 show an example for the brick drying process including a Heat Pump and how the temperature can be varied.

The Rotation Heat Pump (RHP), can achieve more full-load hours with a high COP due to its flexibility in terms of operating range. Due to the lower primary energy consumption, CO_2 emissions can thus be significantly reduced and economic efficiency increased.

FACTS ABOUT THE TECHNOLOGY

Heat supply capacity: 700 kW

Temperature range:

- Max. supply temperature: 150°C
- Max. temperature lift: 40°C (Sink outlet – source inlet), 70°C (Sink outlet – source outlet)
- Max. temperature glide source: 30°C
- Max. temperature glide sink: 30°C

Working fluid: ecop fluid 1

Compressor technology: centrifugal compression

Specific investment cost for installed system without integration: 700€/kW (08/2021)

TRL level: 6/7

Expected lifetime: 20 years

Size: 16 to; 17,8m²

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All information were provided by the supplier without third-party validation. The infomation was provided as an indicative basis and may be different in final installations depending on application specific

Cascade Solution of High Temperature Industrial Heat Pump System With Multiple Functions.

EMERSON

Emerson

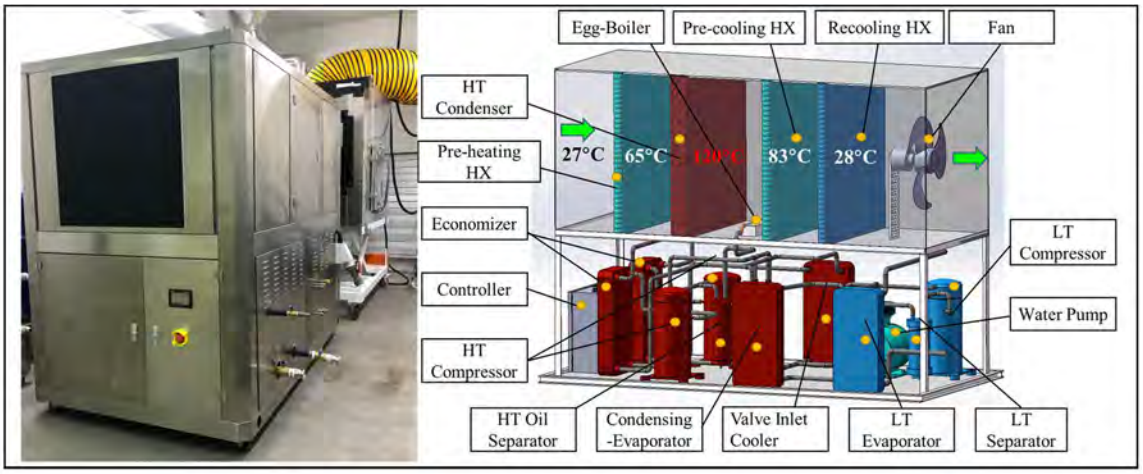

Figure 1: Prototype and Internal Design

Summary of technology

This cascade system is designed for two functions. One is to obtain stable hot air supply at 120°C. It uses Enhanced Vapor Injection (EVI) technology and HT refrigerant flow control valves. Applications include industrial processes requiring hot air above 100℃, such as the coating process of Lithium batteries, PCB board drying, rubber fluid making, etc. The other function of the cascade system is designed to expand multiple heat sources such as industrial wastewater heat recovery or air conditioning processes.
Figure 1 shows the prototype unit.

The system illustrated in figure 2 can be divided into three sections: LT cycle, HT cycle and hot air chamber. The LT cycle consists of a simple loop with R410A refrigerant. It uses an Emerson variable speed compressor, (model ZWW050), and a plate heat exchanger type (PHX) for the evaporator function.
The HT cycle uses the R245fa refrigerant. Two EVI fixed-speed compressors also developed by Emerson specifically for high-temperature applications are installed in parallel. Compared to conventional compressors, their operating envelope is significantly higher.

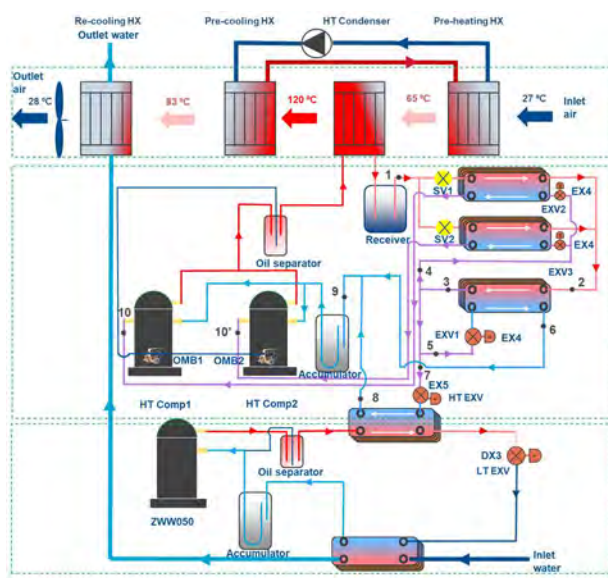

Figure 2: High Temperature Industrial Heat Pump System Layout

A heat recovery water loop is in the hot air chamber, and it is designed for pre-heating and pre-cooling functions of inlet air (designed temperature at 27 °C) to improve the capability and the efficiency of the system.

The re-cooling heat exchanger is just installed to ensure that the outlet air temperature reach a safe temperature level.

The internal heat recovery loop can heat the inlet air up to 65 °C and cool the outlet air down to 83 °C. In real field applications, this function can also be transferred into waste heat recovery of other heat sources.

Emerson offers full solutions for industrial heat pump applications such as high temperature heat pump compressors, high temperature refrigerant flow control parts and advanced oil management solutions.

Project example

Table 1 shows the performances of the cascade system in different conditions, including rated and variable inlet water temperatures.

Based on the performance results, the hot air temperature exceeds 120°C without any problem in these working conditions, which meet the requirements for HT applications. The HT EXV inlet temperature is also successfully controlled below 85°C, which helps to guarantee a reliable operation under high temperature working environments.

Under the working conditions no.1, the heating COP can reach up to 1.74 with a supply air temperature of 121.6 °C, which will bring serious competitive advantages to replace gas and electrical boilers. This HTHP can be also used to leverage low grade heat sources and recover wastewater heat.

Table 1: Performances in Different Conditions

No.	Unit	1	2	3
Inlet Air Temperature	[°C]	27	30	30
Inlet Water Temperature	[°C]	12	20	30
Hot Air Temperature	[°C]	121.6	120	120.2
Heating Capacity	[kW]	29.7	29.9	31.2
Total Compressor Power	[kW]	17.1	19.1	18.3
Heating COP	[-]	1.74	1.57	1.64

FACTS ABOUT THE TECHNOLOGY

Heat supply capacity: 30kW

Temperature range:
Supply temperature 120°C;
Ambient temprature 15~30°C;
Water temperature 10~30°C.

Working fluid: R245fa, R410A*, water

Compressor technology: Sroll & EVI Scroll

Specific investment cost for installed system without integration: Prototype for function and solution demonstration purpose, no cost control.

TRL level: TRL6

Expected lifetime:~15-20 yrs (TBC)

Market Readiness: Expected Availability: 2025

Size: LxWxH= 2.3m x 1.4m x 1.9m, footprint is 3.2 m2

** Low GWP substitution refrigerants will be tested.*

Contact information

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All information were provided by the supplier without third-party validation. The infomation was provided as an indicative basis and may be different in final installations depending on application specific parameters.

enerin ENERGY ENGINEERING

HoegTemp UHT heat pump

Enerin AS

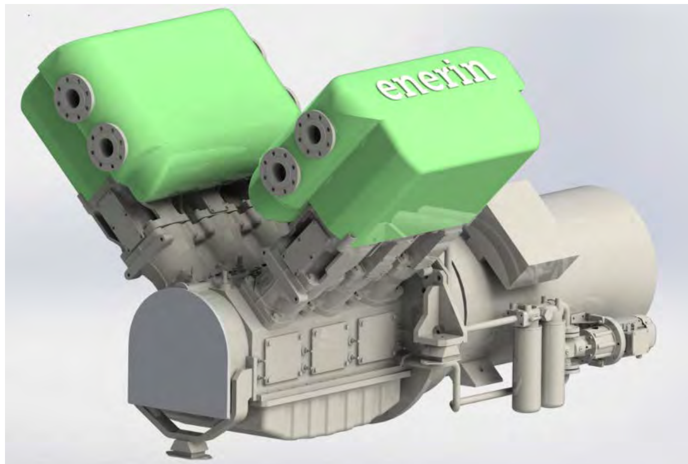

Figure 1: Enerin HoegTemp UHT heat pump

Summary of technology

The HoegTemp heat pump operates on the stirling cycle, with a closed single phase system undergoing compression and expansion by double-acting pistons. Heat exchangers for heat source and heat sink are integrated with the compressors assembly, making up a standard stand-alone unit of 300 to 1000 kW_{th}.

The closed process volume of the heat pump is oil-free, compressor crank and associated systems are lubricated by standard engine oil (0W-50) with integrated oil pump, filters and water cooling.

The HoegTemp heat pump is designed based on more than 30 000 hours of industrial operating experience with prototypes, and it will be qualified for industrial application through pilot installations in 2022 and 2023.

Heat transfer media in secondary circuits will be water based, pressurized water in the hot circuit, glycol/water mix may be used in the cold circuits if the source is close to, or below 0°C. The heat exchangers are welded in AISI 316L stainless steel, and a variety of heat transfer media may be used.

Very short start-up and shut-down times can be achieved, as well as nearly immediate regulation of output. With the design freedom on the heat transfer circuits, combination with heat storage is possible.

Helium (R704) is non-toxic, non-flammable and has zero ODP and GWP. Nitrogen or hydrogen are suitable alternative refrigerants.

Performance data is given in Table 1. COPs were calculated for heating of steam generators making 16 barG and 4 barG steam, from heat sources such as sea water, humid air, and hot cooling water. Published measurements on prototypes show good relation with simulated performance. Lowest COP at peak heat output, highest COP at rated heat output.

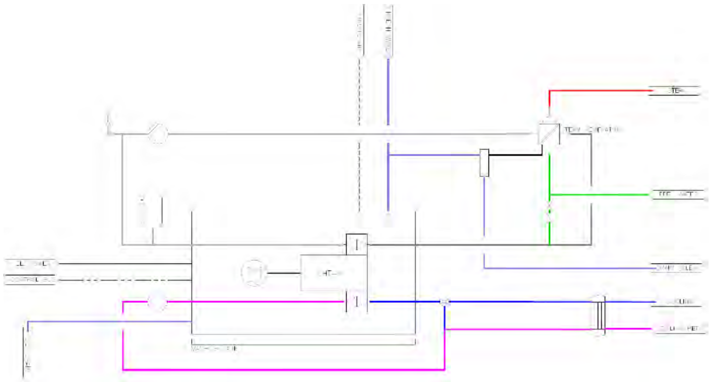

Figure 2: Process diagram of the UHT heat pump

Table 1: Performance.

$T_{source,in}$ [°C]	$T_{source,out}$ [°C]	$T_{sink,in}$ [°C]	$T_{sink,out}$ [°C]	$COP_{heating}$ [-]
85	65	206	212	2.0-2.15
16	12	206	212	1.6-1.7
135	113	154	160	3.3-3.7
80	50	154	160	2.2-2.45
16	12	154	160	1.75-1.9

Project example

Generation of 4 bar_G process steam for an animal feed plant, using humid air with 90% humidity as heat source. The source heat is transferred through a water circuit with high glide, and the heat pump heats a steam generator (shell and plate type) through a pressurized hot-water circuit.

Expected COP is 2.5. Relative to the condensation temperature of the steam, the fraction of carnot COP is 50%. Comparing with the commonly used natural gas boilers with an efficiency of 85%, the ratio between electricity consumption, and a boiler, is 2.95.

Typical operating time per year is 5000 hours. Per MW installed capacity, annual energy consumption is then reduced from 5.9 to 2 GWh/a. With gas and electricity cost at 70 €/MWh, maintenance contract at 10 €/MWh recycled heat, the annual savings are $230 000, while the difference in installation cost compared to a boiler, is $550 000. Annual ROI is 42%. End users evaluating the heat pump for their plants, are satisfied with the expected return on investment, and the expectation for the technology is that it will be scaled to more use cases in the future.

FACTS ABOUT THE TECHNOLOGY

Heat supply capacity: 0.3 MW to 10 MW

Temperature range: Maximum supply temperature 250°C, maximum temperature lift 200°C, minimum source temperature -100°C, temperature glide in hot circuit from 5°C to 40°C, temperature glide in cold circuit from 4°C to 25°C

Working fluid: R704 (He), (N2 may be used with reduced heat output)

Compressor technology: piston

Specific investment cost for installed system without integration: 600 €/kW to 800 €/kW thermal supply capacity

TRL level: TRL 6 (technology demonstrated in relevant environment, >30 000 hours of prototype testing)

Expected lifetime: 20 years.

Size: 10 000 kg, 10 m² (2 m x 5 m) for 1 MW system

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All information were provided by the supplier without third-party validation. The infomation was provided as an indicative basis and may be different in final installations depending on application specific parameters.

High Temperature Heat Pump

enertime

Figure 1: 3.7 MW Enertime Heat Pump on Low-Pressure Steam

Summary of technology

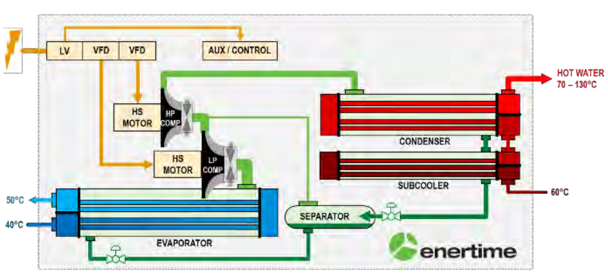
Originating from the design, manufacturing and commercialisation of Organic Rankine Cycle (ORC) machines, ENERTIME proposes High Temperature Heat pumps for large-scale industrial applications (>2 MWth) generating steam, superheated or hot water or direct process heating (process fluid, hot air, …).

Large-scale machines are tailor-made and designed to recover heat from industrial waste heat (cooling loops, process cooling, fumes condensation) and low-temperature resources (greywater, freshwater, seawater, DC networks, …).

The proposed concepts are illustrated in the simplified diagrams below:

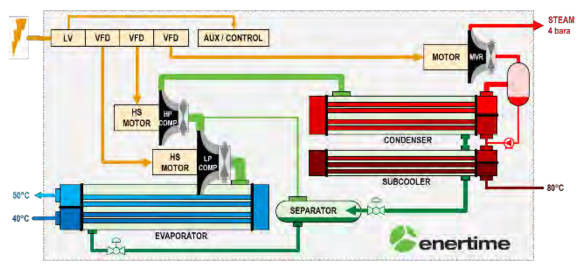
CONCEPT 1 – Superheated / hot water production

For temperatures up to 140°C and lifts up to 80°C.



CONCEPT 2 – Steam generation heat pump

Direct steam generation (max 3 bara & 80°C lifts) or in combination with steam compressor (max 8 bara) from low and medium-temperature resources



CONCEPT 3 – Process heat pump

Tailor-made systems aiming at direct process heating (hot air, process fluid) using medium and low temperature resources (liquid, moist air, process fluid).

MAIN FEATURES

ENERTIME High-temperature heat pumps (HTHP) and steam generators heat pumps (SGHP) provide custom-made solutions adapted to industrial constraints and project needs.

Proposed Heat Pumps are using new-generation non-flammable HFO fluids and custom-made centrifugal compressors adapted to the characteristics of every project with rotation speeds up to 20 000 rpm and compression ratios up to 3.2.

Enertime compressors are using 1 or 2 high speed hermetic motors and magnetic bearing to reach the highest possible performances while ensuring an oil-free, wear-free operation, low vibration rates and low noise emission (<78 dB(A) at 1m) allowing its installation in sensitive areas. Large-scale applications use conventional motors with oil lubricated bearings.

Motocompressors are controlled by AIGV (Automatic Inlet Guide Valves) and VFD (Variable Frequency Drive) to reach the maximal COP, including on non-nominal and partial load operation.

Steam generating heat pumps are coupled with separator tanks and standard steam compressors to generate medium-pressure steam for higher temperature/pressure demand.

COP and performances

Enertime High-Temperature heat pumps are adapted to customer source and sink characteristics while always offering optimal thermodynamic design.

COP generally range between 2.5 to 5 with temperature lifts from 40 to 120°C.

$T_{source,out}$ (°C)	$T_{sink,out}$ (°C)	COP
35	100	3.6
55	120	3.6
60	140	3.3

WORKING FLUIDS

Enertime uses new-generation refrigerants as the working medium for the HTHP. The properties of the refrigerant are optimally adapted to the process requirements in order to achieve high efficiency:

- Chemical stability
- Non-flammable and non-toxic for an easy integration in urban and industrial areas
- Low GWP and ODP
- High critical temperature and low critical pressure
- High volumetric cooling & heating capacity

Selected suitable refrigerants for High Temperature Heat Pumps are listed in the table below:

Type	Refrigerant	T_{crit} (°C)	P_{crit} (bar)	GWP	ODP
HFO	R1336mzzz(Z)	171.3	29.0	2	0
HCFO	R1224yd(Z)	166.5	36.2	1	0
HCFO	R1233zd(E)	155.5	36.3	<1	0

FACTS ABOUT THE TECHNOLOGY

Heat supply capacity: 2 MW to 10 MW

Temperature range: 90°C to 160°C (Steam generation)]

Working fluid: R1336mzzz(Z), R1224yd(Z), R1233zd(E)

Compressor technology: 1 or 2 stage centrifugal hermetic compressor

Specific investment cost for installed system without integration:

- 400€/kW of heat up to 4MW heat production
- 300€/kW of heat from 5MW heat production

TRL level:

- 7-8 concept 1
- 5-6 concept 2
- 4-5 concept 3

Expected lifetime: 20 years

Size: Custom-made depending on project characteristics

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All information were provided by the supplier without third-party validation. The infomation was provided as an indicative basis and may be different in final installations depending on application specific parameters.

MVR-HP

EPCON Evaporation Technology AS

EPCON® Evaporation Technology AS

Figure 1: EPCON standard MVR fan

Summary of technology

The Mechanical Vapor Recompression (MVR) system can have an open or a closed loop layout. It uses water as refrigerant, and features serial compression steps for flexible system design and optimized COP. It is well suitable in a cascade with bottom cycle HP. The driving energy is electricity.

Relevant applications include Industries with existing- or new thermal separation processes as evaporation, distillation and drying, and/or plants with excess applicable thermal energy. MVR can boost temperature and/or generate water steam from district heating hot water loop, for industries using water steam in their processes.

The compression technology consists of high-pressure centrifugal fans or positive displacement blowers. The MVR-HP units are sold using well proven machinery. The fans have been used in MVR evaporators since mid-1980s. They allow for flexible design and operation, e.g. Fast start-up and shut down times. There is no lubrication. New developments include pilot-/demonstration plants together with SINTEF for verifying new type water vapor compressors for lower range capacity.

Suitable source media for MVR-HP is:

- Process vapors, e.g. water vapor, solvent vapor, etc.
- Hot water

Performance data for the MVR-HP system is given in **Table 1**.

The first row refers measured values from an installed system using a single stage MVR roots blower to supply water vapor to a reboiler in a distillation plant.

The second row refers to calculated values from a case study using multiple MVR fans in series in a closed loop.

Figure 2: EPCON compact MVR fans

Table 1: Performance.

$T_{source,in}$ [°C]	$T_{source,out}$ [°C]	$T_{sink,in}$ [°C]	$T_{sink,out}$ [°C]	$COP_{heating}$ [-]
80	80	85	85	13
110	80	110	140	5.5

Project example

An MVR-HP was integrated into an existing distillation process in pharmaceutical industry. Top vapor / alcohol vapor latent heat was used as energy source, while the distillation column bottom reboiler was the energy sink. The MVR-HP was a closed loop system with water as refrigerant. EPCON also supplied the energy recovery- as well as energy supply HX systems.

The commissioning period was very efficient, the MVR-HP start-up and shut-down sequence are smooth and fast, the distillation process operational specifications are not influenced negatively by the MVR-HP. The end-user main performance indicators - energy saving / COP - was achieved from first day of operation. Since the MVR-HP was set in operation, extensions in two steps have been done both to optimize the integration and further to increase the capacity by installing a 2nd similar MVR-HP for another distillation process.

FACTS ABOUT THE TECHNOLOGY

Heat supply capacity: 0.5MW to 100MW
Temperature range: Max supply 150°C, min. source temperature 50°C (if glide, then 50°C is return source temperature). Temperature lift is flexible, however considered versus capacity / return of investment.

Working fluid: Water in closed loop

Compressor technology: High-pressure Centrifugal fan; positive displacement blower.

Specific investment cost for installed system without integration:

- Lower capacity range of 1-3MW, MVR-HP temp. lift of 30-60grdC, specific price 400€/kW.
- Higher capacity range, 10-30MW, MVR-HP temp. lift of 30-60grdC, specific price 200€/kW.

TRL level: 9

Expected lifetime: 25 years

Size: Depends upon capacity / type of MVR machines and temperature lift / number of MVR machines in series. Possible to reduce footprint by stacking MVR machines in 2 or more building levels.

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All information were provided by the supplier without third-party validation. The infomation was provided as an indicative basis and may be different in final installations depending on application specific parameters.

CO_2 Heat Pump System for Hot Water Production

Fenagy A/S

Figure 1: Fenagy H600 heat pump with CO_2 as working fluid.

Summary of technology

The technology from Fenagy is an electric driven heat pump using CO_2 as working fluid and is targeted on district heating and industrial applications. The racks are designed and built according to specific customer needs with thermal supply capacities between 0.3 MW to 1.8 MW.

The energy uptake can be either from air (AW) or water (WW). Reciprocating compressors from either Dorin or Bitzer are typically used, with optional variable speed drive. Internal heat exchangers are used to increase the temperature before the compressor and optimize the performance.

When using CO_2 as a working fluid, the heat pump systems can be made relative compact, and the systems especially has a high potential for applications with large temperature glides, where it is possible for the CO_2 to match the temperature profiles.

For improving the performance in high-temperature applications, Fenagy is currently developing systems with active recovery of the expansion losses.

Case study

A typical application with competitive performances for CO_2 heat pump system is the supply of hot water being heated from 30 °C to a supply temperature of 120 °C. These conditions can be found in well-integrated industrial processes with a high amount of

Figure 2: Fenagy H1800-AW/WW heat pump.

heat recovery, and hence low temperature waste heat.

The calculations for the expected $COP_{heating}$ in such an application are shown in Table 1 for four different operating conditions.

Table 1: Estimated performance.

$T_{source,in}$	$T_{source,out}$	$T_{sink,in}$	$T_{sink,out}$	$COP_{heating}$
[°C]	[°C]	[°C]	[°C]	[-]
0	-5	30	120	2,46
0	-5	30	120	2,61*
5	0	30	120	2,63
5	0	30	110	2,91*

*including expander

The systems are using only medium temperature (MT) compressors due to the low outlet temperature in the gas cooler. The maximum temperature and pressure for the CO_2 in the cycle is around 160 °C and 125 bar(a).

In order to reach highest performances, it is important to recover work from the expansion of the high-pressure refrigerant. This can be done be using an ejector, but concepts for expansion machines are also currently being developed. The estimated performance where an expander is included are also shown in table 1.

FACTS ABOUT THE TECHNOLOGY

Heat supply capacity: 0.3 MW – 1.8 MW

Temperature range: Upper supply limit is 120 °C.

Working fluid: R-744

Compressor technology: Reciprocating.

Specific investment cost for system without integration: 250-425 €/kW

TRL level: For concept study of high temperature application (supply temperature of 120 °C) TRL 5-6 estimated.

Expected lifetime: 20 years

Size: 2.4 m/11.0 m/1.4 m for height/length/ width (valid for 1.8 MW capacity)

Homepage:

https://www.fenagy.dk/en/home

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All information has been provided by the supplier without third-party validation. The information was provided as an indicative basis and may be different in final installations depending on application-specific parameters.

Steam Generation Heat Pump

Fuji Electric

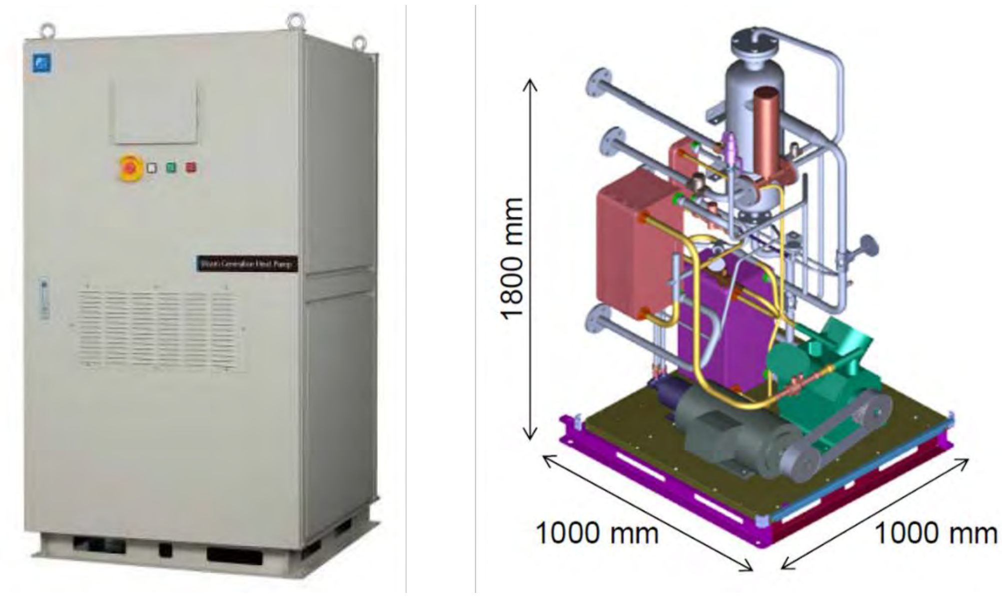

Figure 1: External appearance and element configuration

Summary of technology

The steam generation heat pump was commercialized in 2015. This heat pump can be used as an alternative to the low-pressure steam boiler used for heating processes. The heat pump is expected to install near each heating process. Generally, steam boiler is installed at the energy center located far from each process, and the steam is distributed with long pipes. This causes a lot of heat loss from steam pipes. Installing the heat pump near the process can reduce the heat loss as well as effectively recover the waste heat from the process. For the easy installation near the process, this heat pump is made compact.

The system has a steam generation part and a heat pump cycle part (see Figure 2). The heat pump lifts the heat from the heat source water (60-80°C) and sends the heat to the feed water. The feed water is preheated at the subcooler and evaporated at the condenser. The water is sent to the steam separator in the form of wet steam. Saturated steam (up to 120°C, 0.1 MPaG) from the separator is controlled with the pressure regulator and supplied to a heating process. While saturated water from the separator is mixed with the preheated feed water and returned to the condenser.

For the working fluid of the heat pump, R245fa is selected because of its high critical temperature of 154°C. The compressor is a reciprocating type. The subcooler improves the heat pump cycle efficiency as well as preheats the feed water.

To achieve the compactness, the condenser needs to be smaller. In an existing steam generation heat pump (SGH120 by KOBELCO), saturated steam is generated by decompressing a pressurized water in a flash tank. The pressurized water is heated by refrigerant in the condenser. The condenser needs a larger size because the pressurizes water has a relatively small heat transfer coefficient. In addition, the pressurized water needs to be circulated at a relatively large flow rate, and a pump for pressurized water circulation is required.

On the other hand, the present system selected a two-phase heating method in the condenser. Thanks to the higher heat transfer coefficient of the evaporation of water, the heat transfer area is reduced by 75%, and the condenser can be made compact. The water mass flow

FACTS ABOUT THE TECHNOLOGY

Heat supply capacity: 30 kW/unit (Max. 10 units)

Temperature range: Heat source water 60-80°C, Feed water 10-80°C, Steam 100-120°C

Working fluid: R245fa

Compressor technology: Reciprocating

Specific investment cost for installed system without integration:

TRL level: TRL 9

Expected lifetime: 10 years

Size: Weight 850 kg, Footprint 1.0 m^2

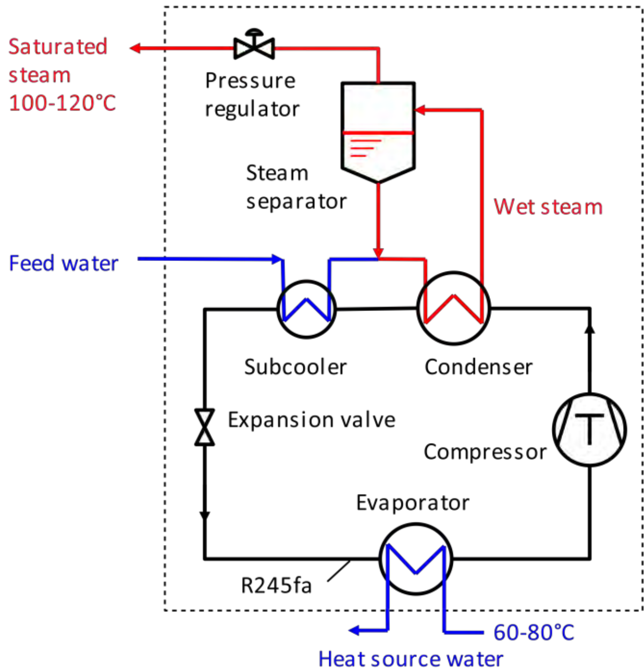

Figure 2: System configuration

Table 1: Performance

$T_{source,in}$ [°C]	$T_{source,out}$ [°C]	$T_{sink,in}$ [°C]	$T_{sink,out}$ [°C]	$COP_{heating}$ [-]
80	70	20	120	3.5
70	62	20	120	2.8
60	54	20	120	2.5

rate is also decreased. Without using a circulation pump, wet steam is sent to the steam separator by a thermosiphon effect.

The rated COP is 3.5 under the heat source water temperature of 80°C and the steam supply temperature of 120°C (see Table 1). The rated heating capacity per unit is 30 kW (45 kg/h of steam), and up to 10 units can be integrated.

Project example

This steam generation heat pump was installed at a cleaning process before painting in a vending machine production factory. The heat pump uses the cleaning wastewater as a heat source and generates steam for heating the cleaning water. To ensure the stable heat source, a wastewater tank was also installed. Compared to the conventional system with steam boiler, this heat pump can reduce energy cost and CO_2 emissions by 52% and 46%, respectively. It should be noted that the reduction effects are values for the part where the heat pump was applied, not for the entire process.

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GEA CO_2 Heat Pump

GEA Heating and Refrigeration Technologies

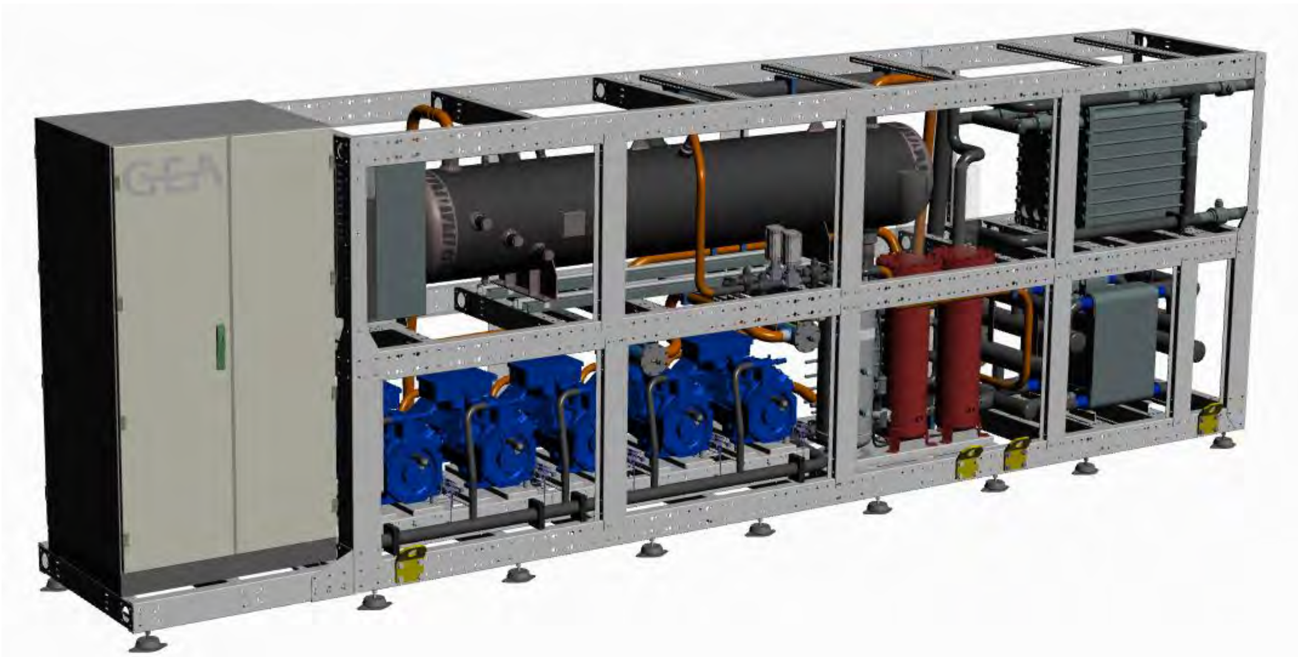

Figure 1: Transcritical chiller with BLUE compressors.

Summary of technology

GEA's high-temperature industrial CO_2 heat pump for combined heating and cooling applications can provide heating water at up to 130 °C.

The unique properties of supercritical CO_2 makes it a favorable choice of heat pumps for heating 'once through' water. It can also be used for heating process water with a low return temperature and high forward temperature. The hot water return temperature ideally should be between 10 °C – 45 °C. The lower the hot water return temperature, the higher the heat pump efficiency.

A GEA CO_2 heat pump for combined heating and cooling gives the largest benefit per kWh of electricity used. With a heating COP of 3 and a cooling COP of 2, it delivers 5 kWh of useful energy per kWh of electricity used. CO_2 is a non-flammable natural refrigerant, with low toxicity and GWP = 1.

The heat pump is constructed with multiple reciprocating transcritical CO_2 compressors (2 – 8) to deliver the required heating and cooling capacities. The heat pump is equipped with a flooded evaporator and separation vessel. The gas coolers can be 1 or 2 heat exchangers in series depending on the temperature lift. For very high temperature lift the intermediate temperature between the high temperature gas cooler (HTGC) and the low temperature gas cooler (LTGC) is optimized to give the best heat pump efficiency.

The heat pump is equipped with GEA Omni control panel which provides state-of-art control of the hot water outlet temperature and the optimal heat pump efficiency. During test the importance of good control of both the heat pump and water system is seen, and since the change of control system to a single controller for both systems a significant efficiency gain during variable operating conditions have been seen.

Table 1 shows the performance of the heat pump in four different operating conditions.

Table 1: Estimated performance.

$T_{source, in}$	$T_{source, out}$	$T_{sink, in}$	$T_{sink, out}$	$COP_{heating}$
[°C]	[°C]	[°C]	[°C]	[-]
6	4	35	120	2.46
12	8	11	90	4.07
10	5	10	95	3.82
20	11	10	95	4.04
10	5	15	98	3.13
6	4	20	130	3.13

Project Example

A prototype of the GEA CO_2 transcritical heat pump has been running since 2019 at GEA's test facilities. The heat pump is producing 130 °C hot water, which is operating in a closed loop returning at 35 °C. At the same time the heat pump is producing chilled water at 4 °C. The chilled water is used for dehumidification and is returning to the heat pump at 10 °C. The prototype heat pump produces 90 kW of hot water at a COP of 3.13.

FACTS ABOUT THE TECHNOLOGY

Heat supply capacity: 0.1 MW – 1.2 MW

Temperature range: Hot water supply temperature from 90˚C to 130˚C. Hot water return temperature from 10˚C to 45˚C. Chilled water/glycol outlet from -10˚C to 25˚C

Working fluid: R-744 (CO_2)

Compressor technology: Semi-hermetic piston

Specific investment cost for system without integration: 200-300 €/kW

TRL level: 8

Expected lifetime: 10 - 15 years

Size: n/a

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HeatBooster
Heaten AS

Figure 1: HeatBooster VHTHP

Summary of Technology

Heaten's patented very-high-temperature heat pump is based on an efficient, durable and highly flexible piston compressor. The HeatBooster turns waste heat into process heat with a value, and is the only technology that can provide an output temperature up to 165 °C.

- The HeatBooster system layout is a one-stage, closed-loop vapor compression heat pump ideal for single or cascade configurations. The heart of the heat pump is a reciprocating compressor.
- The driving energy of the HeatBooster is electricity.
- There are vast opportunities for implementation of Heaten's technology. Some of the relevant applications are district heating, sugar refining, pulp & paper, plastics manufacturing, drying systems and breweries.
- The table below shows typical expected performances under relevant operating conditions. The performance data are based on the actual performance of an industrial 200 kW thermal pilot system, including design and performance improvements.
- Heaten's piston compressor can utilize heavy-duty production tooling and facilities worldwide.
- The HeatBooster uses standard lubricant types that are compatible with the respective working fluids.
- Heaten is currently scaling up the current technology platform to a product family in the megawatt range
- The suitable heat transfer fluid on the source and sink sides is water or steam. The temperature range for the heat source is 2 – 150 °C, and the temperature range for the heat sink is 70 – 200 °C.
- The HeatBooster has a rapid start-up and shut-down time and has a turn-down ratio down to about 20 %. It can handle rapid load changes.
- Standard units span from 1 to 6 MW (can also be delivered as direct-steam version).

Figure 2: HeatBooster compressor

Table 1: Performance.

Example #	$T_{source,in}$ [°C]	$T_{source,out}$ [°C]	$T_{sink,in}$ [°C]	$T_{sink,out}$ [°C]	$COP_{heating}$ [-]
1	80	60	115	120	3,6
2	40	30	80	90	3,3
3	95	85	135	140	4,1
4	120	115	155	165	4,8

Project example

Customer projects are confidential and differ in application and economics, depending on industry needs, customer asks, and regulatory environment.

Heaten's very-high-temperature heat pumps are applied in the following key industries: Paper, food & beverages, chemicals, automotive, metal, plastic, textile, and wood. Key processes are: Drying, boiling, evaporation, sterilization, distillation, molding, cleaning, washing, steaming, tempering, and a long list of specific industrial processes exist, such as bleaching and/or bioreactors.

Please see Table 1. for main performance indicators.

Key success areas for the application of heat pumps are system engineering and integration at customer sites and close cooperation between heat pump suppliers, and customers EPC's.

FACTS ABOUT THE TECHNOLOGY

Heat supply capacity: 1MW nominal.

Temperature range: Up to 165 °C (current hardware is prepared for up to 215 °C)

Working fluid: Most common working fluid including 4th generation refrigerants (HFOs)

Compressor technology: Reciprocating, custom design.

Specific investment cost for installed system without integration: Expected range from 250 to 350€/kW

TRL level: 7-9: Heaten's technology has achieved TRL 9.
TRL 7 refers to the current scaling up of the compressor .

Expected lifetime: Low-maintenance design and service life of 20 years.

Size: Family from 1MW – 6MW. The 1 MW variant fits into a small 20-foot container and the 6 MW heat pump will fit into a normal-size 40 foot container.

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High Temperature Heat Pump

Hybrid Energy

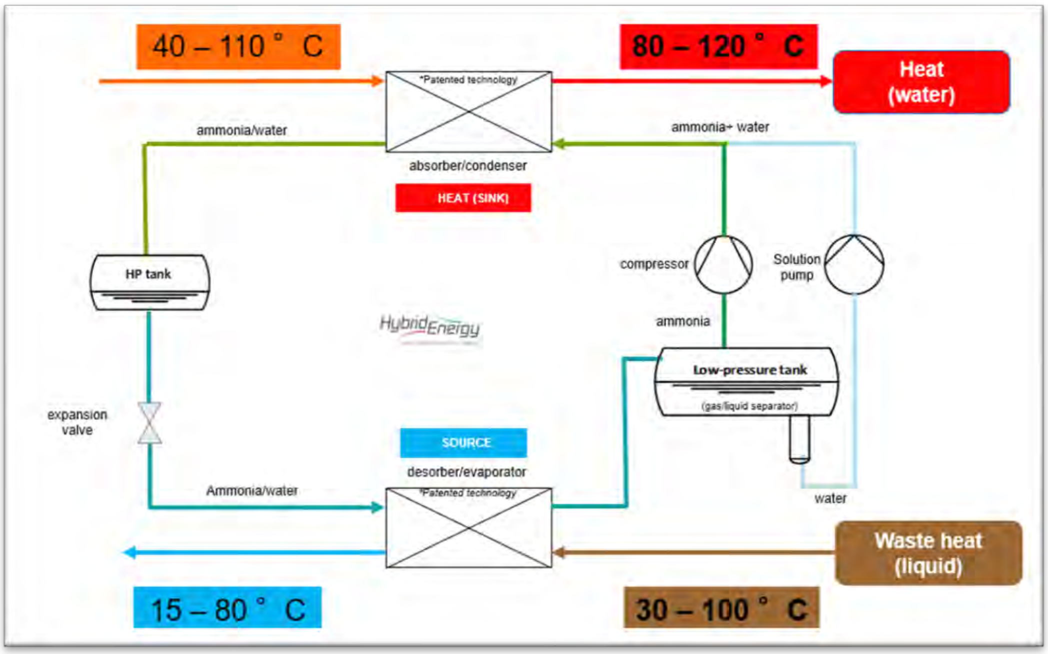

Figure 1: Hybrid technology using both NH_3 & H_2O.

Summary of technology

Hybrid Energy High Temperature heat pumps are based on hybrid technology using ammonia and water as refrigerant. Figure 1 shows the system layout. Key info:

- Two types are available: GreenPAC is a one-stage heat pump and HyPAC is 2-stage.
- For heat pump with high temperature lift, 2 stages (2 compressors) may be required.
- Driving energy: Electrically.
- Refrigerant: NH_3 + H_2O (approx. 50/50).
- Industry segments: Food (dairy, meat, ...), process and waste treatment (biogas ,...)
- Effect:
  - o 0.5 to 2 MW (reciprocation compressors)
  - o 1 to 5 MW (screw compressors)
- Lubrication type and system: Compressor oil with oil filling and drainage.
- Performance see table 1.
- Sink (output) temperatures: 80 – 120 °C.
- Source temperatures: 30 – 100 °C.
- Maximum total temperature lift 90 °C.
- References: 20+ heat pump sold.
- Transport media on sink and source side: Liquid/liquid and rather clean.
- Heat exchanger type: Welded, plate type.
- Pressure: Up to max 40 bars.
- Control system: Siemens S7.
- Hight: max. 5 m.
- Footprint: max. 3.6 x 6.5 m.

Table 1: Performance.

$T_{source,in}$ [°C]	$T_{source,out}$ [°C]	$T_{sink,in}$ [°C]	$T_{sink,out}$ [°C]	$COP_{heating}$ [-]
90	70	90	120	5.6 (calc.)
53	48	65	110	3.6 (calc.)
50	44	65	85	5.5 (meas.)
73	46	70	95	8.1 (meas.)

Figure 2: GreenPAC heat pump at Tine Bergen.

Project example: TINE Bergen (dairy)

TINE was awarded with the Heat Pump City of the year in 2019, category Decarbonization. Project info:

- Turn-key project with chiller, NH_3 heat pump and Hybrid Energy GreenPAC in cascade from -1.5 °C up to 95 °C.
- GreenPAC:
  - Effect 0.9 MW.
  - Source: 67 °C / 60 °C.
  - Sink: 73 °C / 95 °C.
  - COP: 5.5 (measured).
- Conclusions recently published by SINTEF at the high temperature heat pump symposium in Copenhagen March 2022:
  - Successful implementation.
  - System adjusts to varying demands in winter and summer.
  - In winter, TES bridges surplus and deficits.
  - High and almost constant COP's → properly deigned heat pump system.
  - Suitable for other climatic conditions.

FACTS ABOUT THE TECHNOLOGY

Heat supply capacity: 0.5 MW to 2 MW with reciprocating compressor, or 1 MW to 5 MW with screw compressor.

Temperature range: Sink out from 80 °C to 120 °C, with max. temperature lift of 90 °C.

Working fluid: Ammonia and water.

Compressor technology: Piston, screw compressors.

Specific investment cost for installed system without integration: From 200 €/kW up to 600 €/kW depending on the effect and the number of compressors.

TRL level: TRL9 (20+ heat pumps in operation)

Expected lifetime: 20+ years.

Size: Depending on power of the heat pump: max. footprint for 2 MW system is 3.6 m x 6.5 m.

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Cascade Heat Pump System for District Heating

Johnson Controls

Figure 1: ATEX-compliant enclosure for hydrocarbon heat pump.

Summary of technology

The system consists of a cascade heat pump, with R-717 as working fluid in the bottom cycle, and R-600 in the top cycle. The intended application is for district heating. An intermediate cycle with water transfers heat between the two cycles. The heat source for the bottom cycle can be locally available heat sources or, alternatively, an air-cooled evaporator.

The system has reciprocating compressors, which are electrically driven. The compressor design builds on experience from gas transport applications.

The bottom cycle is based on a Sabroe HeatPAC while the top cycle is an ATEX unit with separate enclosure with ventilation and gas detection.

Regarding the lubrication system, an internal oil pump circulates PAG VG 255 oil in the top cycle, while the crankcase optionally can be heated in order to avoid condensation in the compressor suction inlet.

An internal heat exchanger is included to ensure sufficient superheating before the compressor suction side.

Table 1: Performance.

$T_{source,in}$ [°C]	$T_{source,out}$ [°C]	$T_{sink,in}$ [°C]	$T_{sink,out}$ [°C]	$COP_{heating}$ [-]
50	45	70	120	4.3

Figure 2: HeatPAC for NH_3 bottom cycle.

Project examples

Different working fluids have been identified in a project for working at elevated temperatures up to 250 °C or higher. For temperatures from 90 °C to 130 °C, a hydro-carbon working fluid such as n-Butane (R-600) will be a good solution with high COP, low swept volume and low condensing pressure.

For a specific project in Germany, a 27,000 m^3 old coal mine is being explored as a possible heat storage facility. On the surface, different means to heat the water are explored, such as solar heat, which during the summer period is to heat up the water reservoir and use this as a thermal energy storage.

A cascade heat pump system with an ammonia heat pump on the first stage and a Butane heat pump on the second stage is to deliver a high stage temperature of maximum 120 °C at an ambient temperature of -10 °C, and a sink outlet temperature of 80 °C at an ambient temperature of 0 °C.

FACTS ABOUT THE TECHNOLOGY

Heat supply capacity: 0.5 MW (development step 1) to 5 MW (development step 2).

Temperature range: Upper limit is 120 °C (however depending on evaporating temperature).

Working fluid: NH_3 and R-600 (n-Butane).

Compressor technology: Reciprocating.

Specific investment cost for installed system without integration: n/a (highly dependent on actual circumstances, e.g. customs and taxation).

TRL level: NH_3 HeatPAC is proven technology (TRL9), and for R-600 top cycle a little lower TRL level (7-8).

Expected lifetime: 25 years.

Size: Footprint: 6 m long x 1.8 m wide, with a height of under 3 m for each unit (NH_3 and R-600 cycle).

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Micro Steam Recovery Compressor / MSRC160L

KOBELCO Compressors Corporation

Figure 1: External appearance

Summary of technology

The micro steam recovery compressor (MSRC) is a mechanical vapor recompression (MVR) system packaged for general-purpose applications. The MSRC was commercialized in 2011. This system can be used as a steam recovery by compressing the steam which is a flash steam deriving from condensate drain, or low-pressure steam after being used in a heating process.

Steam is used in many industries as a heating medium, In general, steam is produced by heating and evaporating water, and a lot of energy input is necessary for its sensible heat and latent heat. For example, when producing 160°C saturated steam from 20°C water, sensible heat of 591 kJ/kg and latent heat of 2,082 kJ/kg needs to be heated by boiler. Or even if the water supply is preheated using drain water, at least the latent heat of 2,082 kJ/kg needs to be heated by boiler. In contrast, when reusing 110°C low-pressure saturated steam generated at flash tank recovering condensate drain, the needed heat is only latent heat of 66 kJ/kg. Hence the steam recompression can significantly reduce the energy consumption for steam generation.

The MSRC is mainly composed of an oil-free twin-screw compressor and a drain separator. The compressor recovers the low-pressure steam (0.05-0.1 MPaG) and compresses it to a required pressure (0.3-0.8 MPaG). When adiabatically compressing 110°C saturated steam (0.05 MPaG) to 0.5 MPaG, the discharge superheated steam temperature reaches about 264°C. The superheat derived from the compression heat is a large value of 104 K because the saturated temperature at 0.5 MPaG is 160°C. While the rotors of the compressor rotate at high speed with keeping a minute gap for non-contact. Due to the thermal expansion derived from the compression heat, the rotors may come into contact each other. For preventing the superheat of the discharge steam and keeping the clearance between rotor and rotor and between rotor and casing, water is injected into the compressor.

The drain separator is equipped to prevent the injection water that did not evaporate and remained as liquid from being sent out. By removing the water droplet, the compressed steam can be supplied as a form of saturated steam.

The compressor rotating speed can be changed with the inverter in a wide range from 100% to 10%. This enables

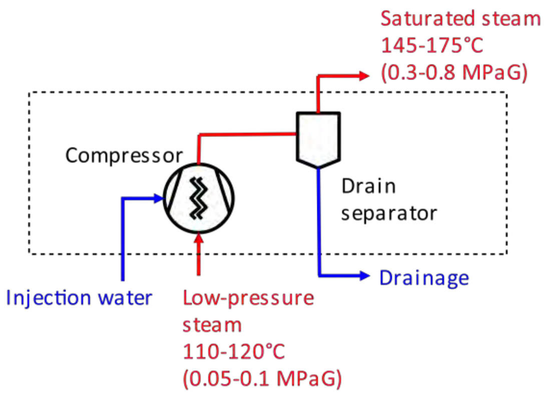

Figure 2: System configuration

Table 1: Performance

T_{source} [°C]	$P_{suction}$ [MPaG]	T_{sink} [°C]	$P_{discharge}$ [MPaG]	$COP_{heating}$* [-]
120	0.1	175	0.8	4.4
120	0.1	152	0.4	6.9
111	0.05	175	0.8	3.1
111	0.05	152	0.4	5.3

* $COP_{heating} = G_{discharge}(h_{discharge} - h_{sat,liq})/W_{el}$

- $G_{discharge}$: Discharge steam mass flow rate [kg/s]
- $h_{discharge}$: Specific enthalpy of saturated steam at discharge pressure [kJ/kg]
- $h_{sat,liq}$: Specific enthalpy of saturated liquid at discharge pressure [kJ/kg]
- W_{el}: Electric power consumption [kW]

the system to follow the steam fluctuation. When the steam demand decreases and the steam pressure decreases, the steam supply flow rates is reduced by decreasing the rotating speed with keeping the discharge steam pressure. The steam supply with stable pressure enables the stable quality of customers products.

The energy performance of the MSRC is listed in Table 1. Both of the suction and discharge steam are saturated steam. To calculate the COP, the enthalpy difference from the discharge saturated steam and the saturated liquid at the discharge pressure is assumed to equal the supply heat.

Project example

More than 25 MSRCs have been installed in steam supply lines in various industries such as paper, chemical and food productions. Here, an example installed in a tissue factory is introduced. In the papermaking process, steam is used for a yankee dryer and condensate is generated. The flash steam from high-temperature drain is thermally compressed with ejector and is directly re-used for drying. While low-temperature 120°C drain was used to preheat the boiler water supply. By using the MSRC, the flash steam from the 120°C drain can be directly re-used for drying. This leads to 5% reduction of the primary energy consumption for the yankee dryer. In response to the good effect, the customer installed another unit.

FACTS ABOUT THE TECHNOLOGY

Heat supply capacity: 800 kW

Temperature range: Suction steam 110-120°C (0.05-0.1 MPaG), Discharge steam 145-175°C (0.3-0.8 MPaG)

Working fluid: R718 (water)

Compressor technology: Twin-screw

Specific investment cost for installed system without integration:

TRL level: TRL 9

Expected lifetime: 15 years

Size: Weight 2,700 kg, Footprint 3.5 m^2

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Steam Grow Heat Pump / SGH120

KOBELCO Compressors Corporation

Figure 1: External appearance of heat pump units (5 units integrated)

Summary of technology

The steam supply heat pump system was commercialized in 2011. This system can be used as an alternative to the low-pressure steam boiler used for heating processes such as distillation of alcohol, concentration of beverage or waste liquid, and sterilization in food industry.

The system is composed of an electrically driven heat pump unit and a flash tank (see Figure 2). The heat pump unit lifts the heat from the heat source water (25-75°C) and sends the heat to the pressurized circulating water. In the flash tank, the pressurized water is decompressed and evaporated. The flash steam (up to 120°C, 0.1 MPaG) is supplied to each process, and make-up water is feed into the flash tank for keeping the water level.

For the working fluid of the heat pump, R245fa is selected because of its high critical temperature of 154°C. As the heat pump cycle, a two-stage economizer cycle with an internal heat exchanger is selected for higher efficiency.

This heat pump equips a two-stage twin-screw compressor which can operate with highly efficiency in a wide range of compression ratio. This enables the high temperature lift operation up to 95 K. The motor cooling method which the refrigerant liquid is directly injected into the motor is adopted so that the motor does not overheat even under high suction temperature conditions. This can achieve both high reliability and performance of the compressor.

Although lubricant oil is necessary for operating a compressor, the oil viscosity generally decreases at high temperatures. The oil is selected so that it has the required viscosity even high temperatures and does not deteriorate and generate sludge.

This system can follow the steam fluctuation. When the steam demand decreases and the steam pressure decreases, the steam supply flow rates is reduced by decreasing the compressor rotating speed with keeping the discharge steam pressure. The steam supply with stable pressure enables the stable quality of customers products.

The rated COP of this system is 3.5 under the heat source water temperature of 65°C and the steam supply temperature of 120°C (see Table 1). The rated heating capacity per unit is 370 kW (0.51 ton/h of steam), and up to 5 units can be integrated.

FACTS ABOUT THE TECHNOLOGY

Heat supply capacity: 370 kW/unit (Max. 5 units)

Temperature range: Heat source water 25-65°C, Feed water 5-95°C, Steam 100-120°C

Working fluid: R245fa

Compressor technology: Two-stage twin-screw

Specific investment cost for installed system without integration:

TRL level: TRL 9

Expected lifetime: 15 years

Size: Weight 4,250 kg, Footprint 6.6 m^2

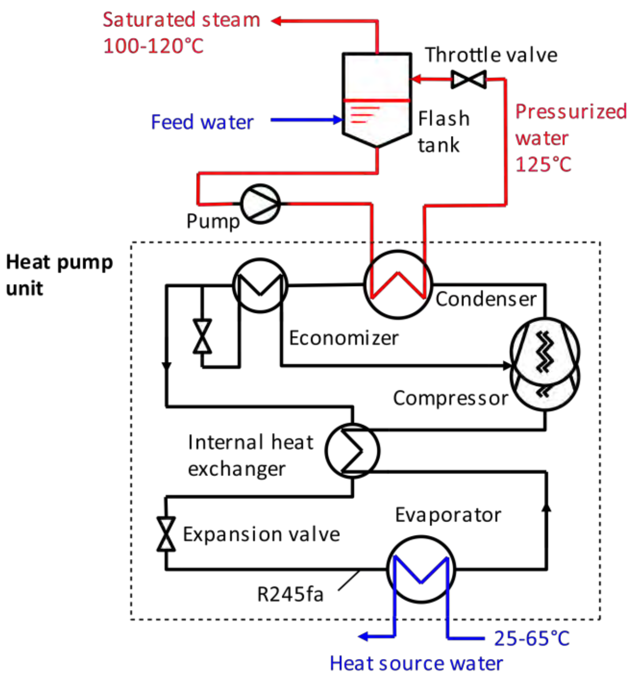

Figure 2: System configuration

Table 1: Performance

$T_{source,in}$ [°C]	$T_{source,out}$ [°C]	$T_{sink,in}$ [°C]	$T_{sink,out}$ [°C]	$COP_{heating}$ [-]
65	60	20	120	3.5
55	55	20	120	3.1
45	45	20	120	2.7
35	35	20	120	2.4

It is desirable that this system is installed near each heating process. Generally, steam boiler is installed at the energy center located far from each process, and the steam is distributed with long pipes. This causes a lot of heat loss from steam pipes. Installing the heat pump near the process can reduce the heat loss as well as effectively recover the waste heat from the process.

Project example

This steam supply heat pump system was installed in a bio-ethanol production plant for the distillation of ethanol in 2013. Before the installation, the distillation column was heated with 120°C steam from heavy oil-fired boiler. Distilled ethanol-rich vapor was condensed with cooling water. For the purpose of heat recovery form the condenser and steam supply to the distillation column, this heat pump system was selected.

With 5 units of the heat pump unit integrated for 1 flash tank, usually 4 units of them operate (1 unit is stopped as a spare), and steam of 2 ton/h are supplied to the distillation column. This amount accounts for 70% of the total steam demand. The remained 30% is covered with the existing boiler. The heat pump can operate at the rated condition and shows the rated COP of 3.5. By reducing the heavy oil consumption for boiler, the operating cost can be reduced by 54% in the total of distillation process.

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Steam Grow Heat Pump / SGH165

KOBELCO

KOBELCO Compressors Corporation

Figure 1: External appearance (steam compressor unit on the left, heat pump unit on the right)

Summary of technology

The steam supply heat pump system was commercialized in 2011. This system can be used as an alternative to the middle-pressure steam boiler used for various heating processes such as drying, sterilization, distillation and concentration.

The system is composed of an electrically driven heat pump unit, a flash tank and a steam compressor unit (see Figure 2). The heat pump unit lifts the heat from the heat source water (35-70°C) and sends the heat to the pressurized circulating water. In the flash tank, the pressurized water at 115°C is decompressed, and the flash steam at 110°C (0.1 MPaG) is generated. The steam compressor unit compresses the steam up to 175°C (0.8 MPaG) with injecting water. The saturated steam is supplied to each process, and make-up water is feed into the flash tank for keeping the water level.

For the working fluid of the heat pump, the mixture of R245fa and R134a is selected for achieving a good performance. As the heat pump cycle, an economizer cycle with an internal heat exchanger is selected for higher efficiency.

The heat pump unit equips a twin-screw compressor which is optimized in a certain range of compression ratio. The lubricant oil is selected so that it has the required viscosity even high temperatures and does not deteriorate and generate sludge.

The steam compressor is an oil-free twin-screw compressor. For preventing the superheat of the discharge steam and keeping the clearance between rotor and rotor and between rotor and casing, water is injected into the compressor.

This system can follow the steam fluctuation. When the steam demand decreases and the steam pressure decreases, the steam supply flow rates is reduced by decreasing the both compressors' rotating speeds with keeping the discharge steam pressure. The steam supply with stable pressure enables the stable quality of customers products.

The rated COP of this system is 2.5 under the heat source water temperature of 70°C and the steam supply

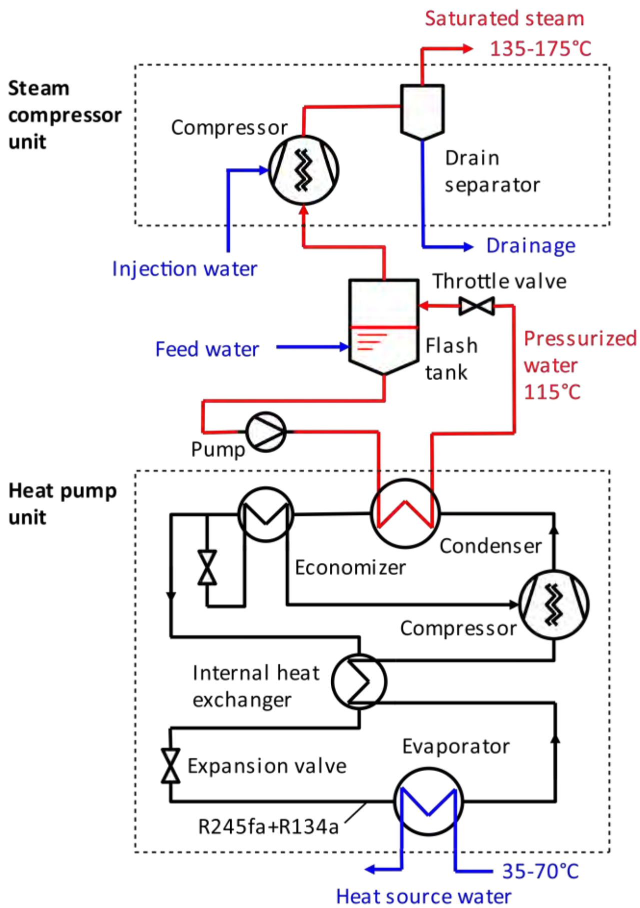

Figure 2: System configuration

Table 1: Performance

$T_{source,in}$ [°C]	$T_{source,out}$ [°C]	$T_{sink,in}$ [°C]	$T_{sink,out}$ [°C]	$COP_{heating}$ [-]
70	65	20	165	2.5
70	65	20	135	3.0
50	45	20	165	1.9
50	45	20	135	2.2

temperature of 165°C (see Table 1). The rated heating capacity per unit is 624 kW (0.84 ton/h of steam).

It is desirable that this system is installed near each heating process. Generally, steam boiler is installed at the energy center located far from each process. This causes a lot of heat loss from steam pipes. Installing the heat pump near the process can reduce the heat loss as well as effectively recover the waste heat from the process.

FACTS ABOUT THE TECHNOLOGY

Heat supply capacity: 624 kW

Temperature range: Heat source water 35-70°C, Feed water 5-95°C, Steam 135-175°C

Working fluid: R245fa+R134a (mixture) for heat pump unit, R718 for steam compressor unit

Compressor technology: Twin-screw

Specific investment cost for installed system without integration:

TRL level: TRL 9

Expected lifetime: 15 years

Size: Weight 7,050 kg, Footprint 13.8 m^2

Project example

The SGH165 was installed at CRIEPI (Central Research Institute of Electric Power Industry) lab in 2013. On the assumption of actual different industrial process temperatures, the energy performance data were obtained under various heat source temperatures, feed water temperatures and steam discharge temperatures. In addition, the control performances including the start-up and shut-down operations, the condensed water blow operation, and the load-following capability were obtained. After the performance evaluation and reliability test, some units were installed in actual factories.

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ETES CO_2 Heat pump

MAN Energy Solutions

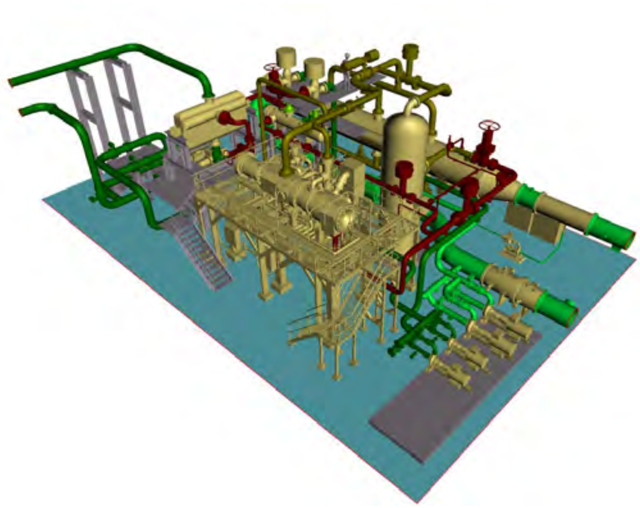

Figure 1: Typical heat pump system general arrangement

Summary of technology

The MAN high temperature industrial heat pump system has been derived from the Electro-Thermal Energy Storage technology developed originally by ABB and further developed by MAN Energy Solutions. The working fluid is CO_2 operated in an optimized trans-critical heat pump cycle.

The system is customized to the specific customer requirements for several applications in three frame sizes (small-middle-large) depending on the duty varying between 10 to 50 MW thermal supply capacity per unit. Typical applications are for district heating plants and process industry applications demanding medium to high supply temperatures (up to 150°C).

The design and heat pump layout is fully customizable and adapted to each project or specific site requirement. The main piece of equipment is a hermetically sealed centrifugal turbo-compressor driven by high speed electrical drive incl. VSD (variable frequency drive).
The overall system is closed and emission-free. An expander stage is integrated for optimal performance. The rotating parts on magnetic bearings makes the system oil-free and maintenance friendly (no wear and tear parts hence low specific OPEX resp. maintenance effort).

The static process equipment parts (i.e. heat exchangers) are optimized resp. customized to reach the required duty and performance while complying the specific space requirements. Special compact heat exchangers are therefore applied on the sink side.

The performance of the system (i.e. COP) depends mainly on the temperatures applied, primarily the supply and return temperature on the sink side, secondly the temperature level of the source medium (mainly water).

A pilot system of 5MW heat supply capacity was successfully tested at the MAN production & testing facility in Zurich in 2020 and two units have been sold in 2021 for a district heating application.

Due to the use of CO_2 as refrigerant, the source medium temperature cannot be elevated much more than 40°C, however a temperature lift up to 150-170°C can be achieved with the single-stage heat pump system. The system takes benefit of the favorable compressing properties of CO_2 and its outstanding heat transfer capacities when compressed to supercritical conditions (i.e. above 78.4 bar).

The units can be combined with storage tanks making the system even more flexible in operation (daily charging / discharging cycles typically).

Start-up and shut-down times are very short due to active magnetic bearing technology. Likewise dynamic or fast load change capability for grid stabilization purpose can improve the overall operational profitability of the heat pump system.

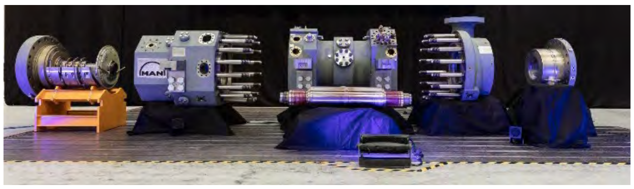

Figure 2: Compressor HOFIM™ dismantled

Table 1: Performance for different conditions

$T_{source,in}$ [°C]	$T_{source,out}$ [°C]	$T_{sink,in}$ [°C]	$T_{sink,out}$ [°C]	$COP_{heating}$ * [-]
10	7	40	110	3.05
2	-1	30	95	3.25
20	17	50	150	2.85

**) calculated (i.e. predicted) values*

Project example

Two heat pump units will be installed in the city of Esbjerg in Denmark by end of 2022 for replacing the current coal-fired power plant by mid 2023 for a carbon neutral district heating supply of all neighboring communes. The installed units have an overall thermal supply capacity of >50MW with a COP>3.

Similar project are under development mainly in Europe but also worldwide.

All information were provided by the supplier without third-party validation. The infomation was provided as an indicative basis and may be different in final installations depending on application specific parameters.

FACTS ABOUT THE TECHNOLOGY

Heat supply capacity: from 10 MW to 50 MW per unit

Temperature range: sink temperature up to 150°C, source temp. from -20° up to 40°C, max. temperatur lift of approx. 170 K

Working fluid: CO_2

Compressor technology: centrifugal turbo-compressor (hermetically sealed) with integrated expander

Specific investment cost for installed system without integration: 300 – 500 €/kW (thermal supply capacity)

TRL level: 7-8 (prototype tested in 2020, project in execution in 2021)

Expected lifetime: approx. 35 years

Size: from 100 m^2 (smallest unit) to 250 m^2 (biggest unit) with max. 10 kN/m^2

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Hydrocarbon Heat Pump / FC-compressor

Mayekawa Europe NV

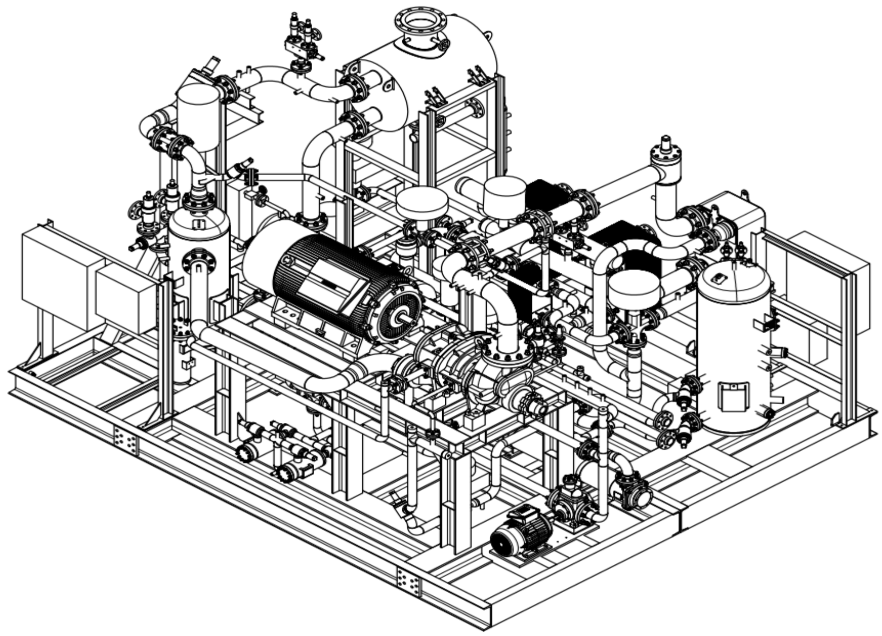

Figure 1: General layout

Summary of technology

In steam generating applications the heat is commonly produced by combustion. This FC compressor heat pump package was specifically developed to replace or reduce the use of the burners by generating steam up to 145°C.

The heat pump is a closed loop plug & play package which uses water as the heat source medium.

The heat source temperature is considered to be 90 °C and the heat source outlet temperature approximately 85°C, focusing primarily on heat recovery from water.

At the heat sink side, the heat pump will boil 90°C supplied water up to 145°C steam.

To achieve high efficiencies and a low GWP, Pentane (R601) is considered as refrigerant. The use of R601 refrigerant results in very low operating pressures combined with high operating temperatures, which allows the use of conventional refrigeration compressors with some minor modifications.

The compressor is an oil lubricated screw type with a heating capacity of around 1000 kW. The compressor is driven by an electromotor. The heating capacity can be modified by changing the rotational speed of the motor with an inverter and during start-up/turndown by means of the mechanical slide valve.

Although it is possible to use several types of alternative heat exchanger technology on the heat source side, a water-to-refrigerant heat exchanger was selected because of the reduced footprint and the ease to recover heat from other/remote processes and transport it to the heat pump.

Due to the high discharge gas temperature, a separated oil circuit is used. The bearing oil lubrication is a separate closed loop system maintained at lower temperature with a focus on degassing the oil before supplying it to the compressor bearings. The oil injection circuit is a conventional oil lubrication cycle designed in order to recover the oil from the discharge gas and resupply it to the compressor rotors for optimal efficiency on the gas compression.

Both oil circuits and the oil return system from low temperature liquid receiver side are integrated within the heat pump package.

A secondary outboard shaft seal with Nitrogen flushing with safety monitoring is installed on the compressor in order to minimize the hazard of flammable gas leakage into the machine room.

Performance of the heat pump is shown in Table 1. The COP is calculated theoretically by means of our in-house empirically developed compressor selection software. It does not yet consider additional electrical losses & power consumption of auxiliary equipment.

Table 1: Performance.

$T_{source,in}$ [°C]	$T_{source,out}$ [°C]	$T_{sink,in}$ [°C]	$T_{sink,out}$ [°C]	$COP_{heating}$ [-]
90	85	90	145	2.6

Project example

Technology has been validated in relevant environment and is currently in preparation for demonstration in relevant environment by autumn of 2022.

FACTS ABOUT THE TECHNOLOGY

Heat supply capacity: 1000 kW

Temperature range: Tsource, out 85°C and Tsink, out 145°C steam

Working fluid: R601

Compressor technology: Screw

Specific investment cost for installed system without integration: +/- 720€/kW

TRL level: 5

Expected lifetime: 20 years

Size: 20000 kg, 25 m² footprint

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Hydrocarbon Heat Pump / HS-compressor

Mayekawa Europe NV

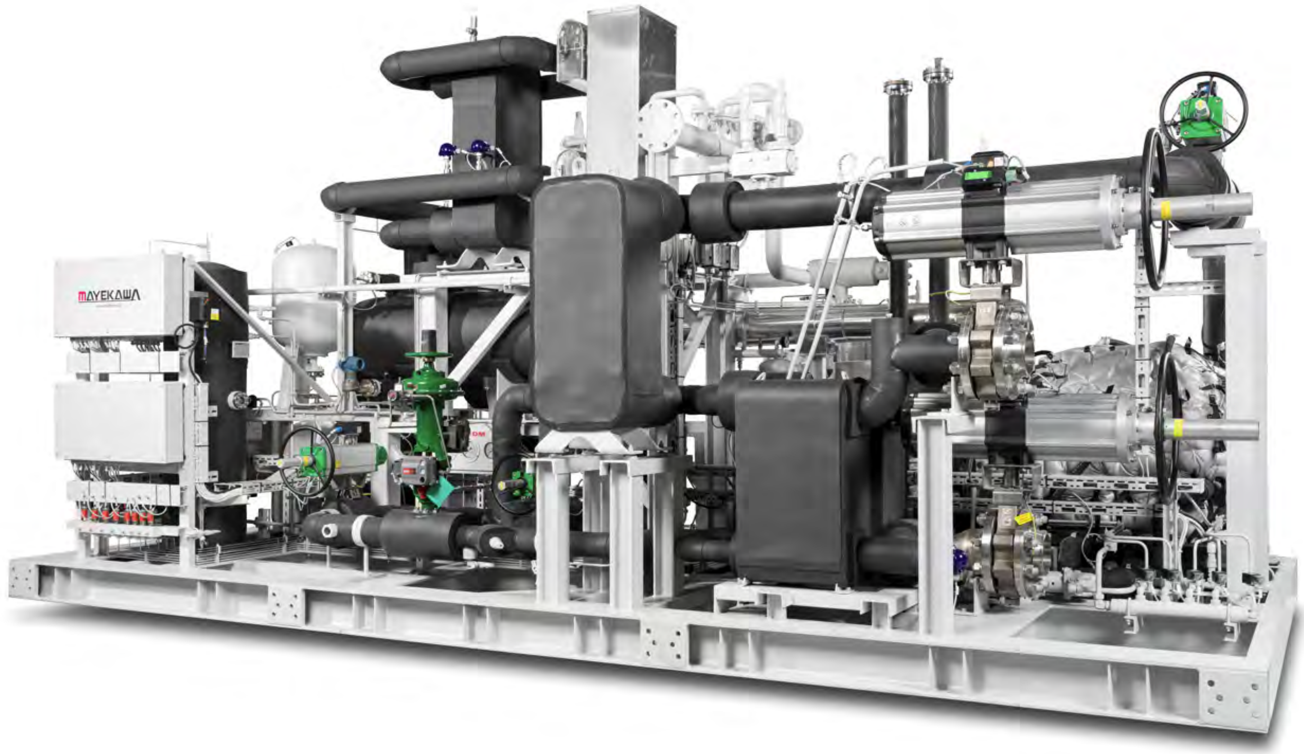

Figure 1: General layout

Summary of technology

In district heating applications the heat is commonly produced by combustion. This HS compressor heat pump package was specifically developed to replace or reduce the use of the burners by supplying hot brine up to 120°C.

The heat pump is a closed loop plug & play package which uses water as the heat source medium.

The heat source temperature is considered to be 72 °C and the heat source outlet temperature can vary between 45 and 65 °C, focusing primarily on heat recovery from water.

At the heat sink side, the heat pump heats water from 70°C to 120°C.

To achieve high efficiencies and a low GWP, Butane (R600) is considered as refrigerant. The use of R600 refrigerant results in low operating pressures combined with high operating temperatures, which allows the use of conventional refrigeration compressors.

The compressor is a reciprocating type with a heating capacity of around 750 kW. The compressor is driven by an electromotor. The heating capacity can be modified by changing the rotational speed of the motor with an inverter.

Although it is possible to use several types of alternative heat exchanger technology on the heat source side, a water-to-refrigerant heat exchanger was selected because of the reduced footprint and the ease to recover heat from other/remote processes and transport it to the heat pump.

The oil lubrication and recovery system are integrated within the heat pump package and the entire skid is installed into a ventilated enclosure by customer request.

Figure 2: Plug & play heat pump

Performance of the heat pump is shown in Table 1. The COP is calculated theoretically by means of our in-house empirically developed compressor selection software. It does not consider additional electrical losses & power consumption of auxiliary equipment.

Table 1: Performance.

$T_{source,in}$ [°C]	$T_{source,out}$ [°C]	$T_{sink,in}$ [°C]	$T_{sink,out}$ [°C]	$COP_{heating}$ [-]
72	65	70	120	4.8
72	60	70	120	4.4
72	55	70	120	4
72	50	70	120	3.7
72	45	70	120	3.2

Project example

The heat pump is currently installed, commissioned and being demonstrated in an application to recover heat from condensed steam from turbines of around 70°C and supply hot water of around 120°C into the district heating network.

FACTS ABOUT THE TECHNOLOGY

Heat supply capacity: 750 kW

Temperature range: Tsource, out 45-65°C and Tsink, out 120°C

Working fluid: R600

Compressor technology: Piston

Specific investment cost for installed system without integration: +/- 450€/kW

TRL level: 7

Expected lifetime: 20 years

Size: 13750 kg, 18 m² footprint

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CO_2 Air Heater Heat Pump / Eco Sirocco

Mayekawa Mfg.

Figure 1: External appearance

Summary of technology

In hot air drying processes, hot air is commonly produced by gas burners or steam boilers. The Eco Sirocco air heater heat pump was developed to replace or reduce use of the gas burners and boilers by supplying hot air up to 120°C, or act as a preheater when the drying temperature is above 120°C.The heat pump was commercialized in 2009 and is applicable in both drying and dehumidifying processes.

The heat pump uses water or brine as the heat source medium (see Figure 2). The heat source temperature is of a wide range from 0°C to 40°C, which realizes two types of heat recovery, wastewater or chilled water supply. At the heat sink side, the heat pump heats ambient air of (-10-43°C) and supplies hot air of (60-120°C).

The heat sink temperature glide is large. To achieve higher efficiencies a transcritical heat pump cycle is used. R744 (CO_2), with critical temperature and pressure of 31.0°C and 7.38 MPa, is used as the refrigerant.

Use of R744 as the refrigerant results in high operating pressures. The maximum suction and discharge pressures are 7 MPa and 15 MPa, respectively. The compressor is a reciprocating type. The heating capacity is about 100 kW.

The heating capacity can be varied by changing the rotation speed of the compressor with an inverter.

The gas cooler (air heater) consists of aluminum-fin, copper-tube heat exchanger, and is designed for high pressure specifications up to 15 MPa. The maximum air flow rate is 8,500 m^3/h.

It is possible to use an air-to-refrigerant heat exchanger on the heat source side when recovering heat from the dryer exhaust air. However, a water-to-refrigerant heat exchanger was selected because of the following reasons:

- An air-to-refrigerant heat exchanger requires an air duct which is not easily installed and is complicated to handle.
- It is easier to recover heat from other processes or generated chilled water can be supplied to other processes when using a water-to-refrigerant heat exchanger.

Performance of the heat pump is shown in Table 1. As shown, this heat pump is suitable for application in drying processes with large temperature glides at the heat sink.

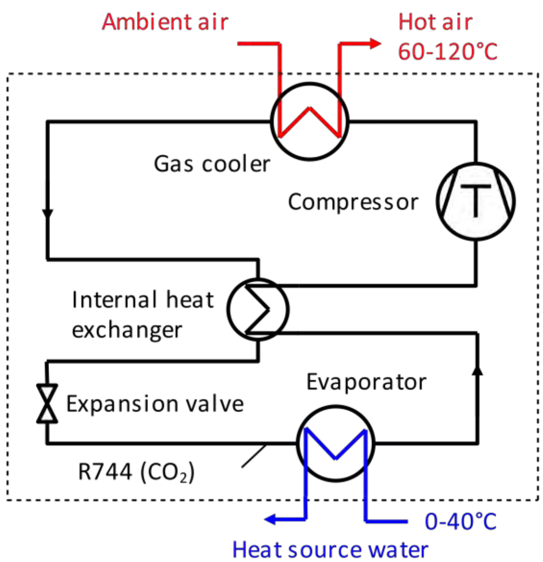

Figure 2: System configuration

Table 1: Performance

$T_{source,in}$ [°C]	$T_{source,out}$ [°C]	$T_{sink,in}$ [°C]	$T_{sink,out}$ [°C]	$COP_{heating}$ [-]
30	25	20	120	3.1
30	25	20	100	3.7
30	25	20	80	4.5
30	25	20	60	5.5

Project example

More than 90 units of this hot air supply heat pump have been installed in various drying processes such as paint drying of electric transformers, laminating of plastic films, and regeneration of the desiccant dehumidifier.

As an example, the heat pump was applied to provide part of the heat load needed in drying of electric transformer casings after paint coating. The drying process needs hot air of 170°C and 150°C. Previously, LPG (liquefied petroleum gas) burners were used to provide hot air. Application of the heat pump to provide hot air up to 120°C reduced use of LPG.

On the other hand, paint used in the electrodeposition coating process has to be maintained at a constant temperature. Chilled water produced at the heat source side is used.

FACTS ABOUT THE TECHNOLOGY

Heat supply capacity: 100 kW

Temperature range: Heat source water (or brine) 0-40°C, Ambient air -10-43°C, Hot air 60-120°C

Working fluid: R744 (CO_2)

Compressor technology: Reciprocating

Specific investment cost for installed system without integration:

TRL level: TRL 9

Expected lifetime: 15 years

Size: Weight 1,750 kg, Footprint 1.7 m^2

The heat pump, therefore, saves energy by reducing electric consumption of the existing chiller as well as reduction in LPG consumption.

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Information here in was provided by the supplier without third-party validation. Infomation was provided as an indicative basis and may be different in final installations depending on application specification parameters.

Hot Air Circulation Heat Pump / Eco Circuit 100

Mayekawa Mfg.

Figure 1: External appearance

Summary of technology

Mayekawa commercialized a one way CO_2 air heater heat pump (Eco Sirocco) in 2009 and a hot air circulation heat pump (Eco Circuit) in 2018. Eco Sirocco is suitable for application in dry processes with large temperature glides at the heat sink, and supplies hot air up to 120°C. On the other hand, the Eco Circuit is suitable for application in dry processes with small temperature glides at the heat sink, and supplies hot air up to 85°C.

A new product Eco Circuit 100 was commercialized in 2021. This heat pump supplies hot air up to 100°C as a result of improving the existing Eco Circuit. The higher supply temperature expands application of the heat pump in more drying processes.

The Eco Circuit 100 targets applications such as paint drying of resin products which require about 95°C hot air and cannot be serviced the existing Eco Circuit which supplies air up to 85°C. The Eco Circuit 100 was newly developed for such customer needs.

The heat pump uses water or brine as the heat source medium (see Figure 2). The heat source temperature is of a wide range from 0°C to 40°C, which realizes two types of heat recovery from wastewater or chilled water. At the heat sink side, the heat pump heats return air from the dryer (with a small temperature glide) up to 100°C.

R1234ze(E), which has a small GWP below 1, is used as the refrigerant. The critical temperature is 109.4°C. The heat pump operates in the subcritical region.

The compressor is a reciprocating type. The heating capacity is about 100 kW. The heat pump is controlled so that supply hot air temperature is kept constant.

The condenser (air heater) consists of an aluminum-fin, copper-tube heat exchanger. The maximum air flow rate is 45,000 m^3/h.

The evaporator is a plate type heat exchanger. Wastewater from other processes, cooling water for chillers or air compressors can be used in the heat source. By lowering the evaporation temperature, both chilled water and hot air can be supplied from the heat source and heat sink sides simultaneously.

Performance of the heat pump is shown in Table 1. As shown in the table, the heat sink temperature glide is preferably about 10 K or less.

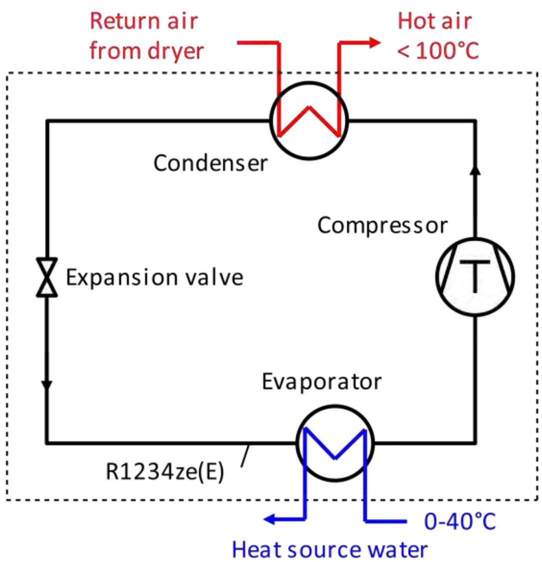

Figure 2: System configuration

Table 1: Performance

$T_{source,in}$ [°C]	$T_{source,out}$ [°C]	$T_{sink,in}$ [°C]	$T_{sink,out}$ [°C]	$COP_{heating}$ [-]
30	25	90	100	2.6
30	25	80	90	2.8
30	25	70	80	3.2

Project example

Eco Circuit, which supplies hot air up to 85°C, was installed for high temperature aging process in Li-ion battery production. The heat pump is used for keeping the aging room temperature constant.

On the other hand, Eco Circuit 100, which heats air up to 100°C, has just been commercialized and has not been installed in any factory as yet. It is expected to be introduced in drying processes of resin products in the future. There is cooling every after a drying process, therefore, simultaneous heating and cooling can be realized.

FACTS ABOUT THE TECHNOLOGY

Heat supply capacity: 100 kW

Temperature range: Heat source water (or brine) 0-40°C, Inlet air 50-100°C, Hot air <100°C

Working fluid: R1234ze(E)

Compressor technology: reciprocating type

Specific investment cost for installed system without integration:

TRL level: TRL 8-9

Expected lifetime: 15 years

Size: Weight 5,500 kg, Footprint 7 m^2

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130°C Hot Water Supply Heat Pump / ETW-S

Mitsubishi Heavy Industries Thermal Systems

Figure 1: External appearance

Summary of technology

The hot water supply heat pump was commercialized in 2011. This heat pump can supply pressurized water of 130°C and can be applied for heating processes such as drying and sterilization.

This heat pump uses water as both of the heat source and heat sink media (see Figure 2). At the design point, the heat source temperature is 55°C inlet / 50°C outlet, and the heat sink temperature is 70°C inlet / 130°C outlet.

The heat sink temperature glide is large. For higher efficiency, a transcritical heat pump cycle is selected. R134a, which critical temperature and pressure are 101.1°C and 4.06 MPa, is used as the refrigerant.

This heat pump equips a two-stage centrifugal compressor. For higher efficiency, impellers with different sizes are used for the 1st and 2nd stages. Considering thermal expansion due to a large temperature difference between when stopped and when operating, carbon steel, which has a smaller coefficient of linear expansion than aluminum, is selected as the material of the impeller. This can keep the clearance between the impeller and the shroud and prevent deterioration of the compression efficiency. Carbon steel also has a higher strength, which can prevent deformation of the impeller tip. The maximum rotating speed is 42,000 rpm.

The gas cooler is a brazing plate heat exchanger designed for high pressure and temperature specifications more than 5 MPa and 145°C.

By introducing an intercooler, compressor suction vapor is superheated with gas cooler outlet refrigerant. This can reduce compressor discharge pressure, while keeping the high discharge temperature.

The heating COP is 3.0 at the design point (see Table 1). The COP decreases under part-load conditions. When the heating capacity is 250 (40% part-load), the COP is 2. The heating capacity is 627 kW, which is almost equivalent to steam of 1 ton/h.

Project example

The heat pump was installed in an electric transformer production factory for a drying process of the coil. The coil of electric transformer has copper wire and paper coated with a special resin. By heating the coil, the resin melts and the paper and the copper wire adhere.

In the previous system, steam boiler was used for producing hot air. And the exhaust gas from the dryer had

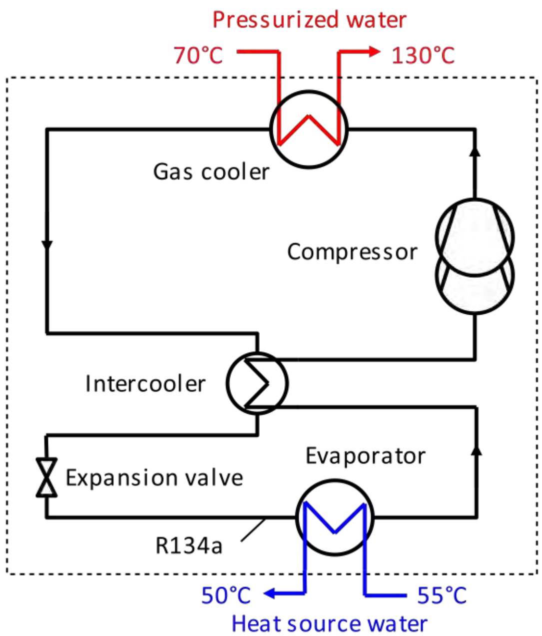

Figure 2: System configuration

Table 1: Performance

$T_{source,in}$ [°C]	$T_{source,out}$ [°C]	$T_{sink,in}$ [°C]	$T_{sink,out}$ [°C]	$COP_{heating}$ [-]
55	50	70	130	3.0

relatively high temperature, but not recovered. Likewise, in another process (annealing process), there was waste heat.

In the new system, the heat pump was installed. The heat pump uses both exhaust heats from drying process and annealing process as the heat source. However, the operation time of the annealing process is not the same at the drying process. Hence a thermal storage tank was also installed for securing the stable heat source of the heat pump. This heat pump supplies 130°C pressurized water, and then produces 125°C hot air with heat exchange. The previous boiler is used for the backup.

The total waste heat of the drying process and the annealing process is about 420 kW at the time average value. It is sufficient for the heat source. The heat pump can supply all the heat needed for the drying without using the backup boiler.

FACTS ABOUT THE TECHNOLOGY

Heat supply capacity: 627 kW

Temperature range: Heat source water 55°C, Pressurized hot water 130°C

Working fluid: R134a

Compressor technology: two-stage centrifugal

Specific investment cost for installed system without integration:

TRL level: TRL 9

Expected lifetime: 15 years

Size: Weight 6,500 kg, Footprint 7.7 m^2

The heat pump can operate at the COP of 3. Compared to the conventional system with natural gas-fired steam boiler, CO_2 emissions and energy cost can be decreased by 60% and 65%, respectively.

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Ohmia Industry

Steam producing heat pump (SPHP)

Ohmia Industry AS

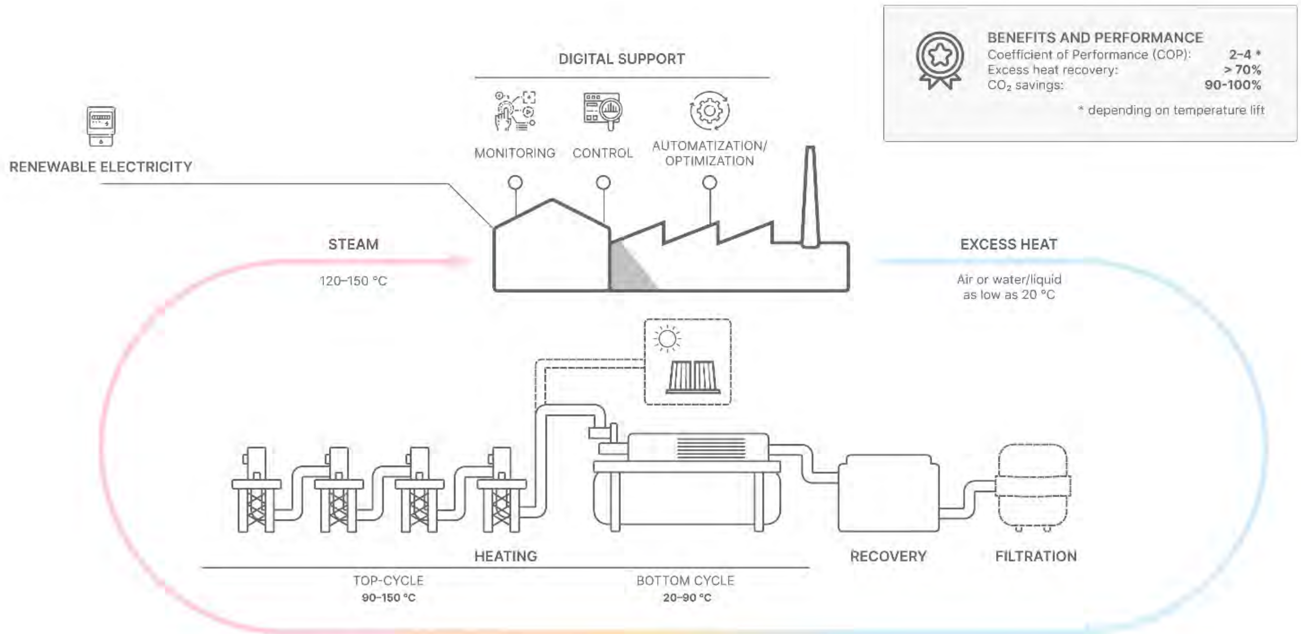

Figure 1: Steam producing heat pump (SPHP) with excess heat recovery and multi-stage compression.

Summary of technology

The core technology of Ohmia Industry is an integrated heat pump system which can supply process heat in the form of pressurized steam of up to 150°C or 5 barA. The steam producing heat pump (SPHP) is standardized for excess heat temperatures between 20°C and 90°C. The SPHP integration includes an energy recovery unit for moist air, however also other excess heat sources can be integrated.

The recovered heat is transferred to a bottom cycle which upgrades the energy into low pressure steam. The bottom cycle uses Ammonia (R717) as working media. The low-pressure steam is further compressed by multistage steam compressors and can reach up to 5 barA/150°C. The multistage cascading also enables the usage of steam (or hot water) at lower temperatures or pressure levels which improves the COP of the system.

The principal layout of the SPHP is given in Figure 1 and is a combination of a closed loop bottom cycle and an open loop top cycle (typically known as Mechanical Vapor Recompression). The top cycle can also be integrated as closed loop according to process requirements.

The most relevant application areas are in the food, pulp and paper as well as chemical industry for processes like drying, evaporation, sterilization, thermal treatments or similar processes. However, also other application, process and plant integrations are possible.

The SPHP uses natural refrigerants such as Ammonia and Water as working media and heat carrier. Compressor types are centrifugal fans for the top-cycles and piston compressors for the bottom cycle. The pilot system is a 1.5 MW steam producing heat pump which is currently under installation and will start-up end of 2022.

Ohmia Industry is establishing and operating the SPHP systems onsite for customers through an "Energy as a Service" platform. The technology, integration, investment, reliability, and technical risk as well as the service costs are hereby covered by Ohmia Industry. The customer pays for the energy supplied by the SPHP system.

Currently the system is only available in Norway, however from 2023 also other costumers in the EU can be equipped with the system.

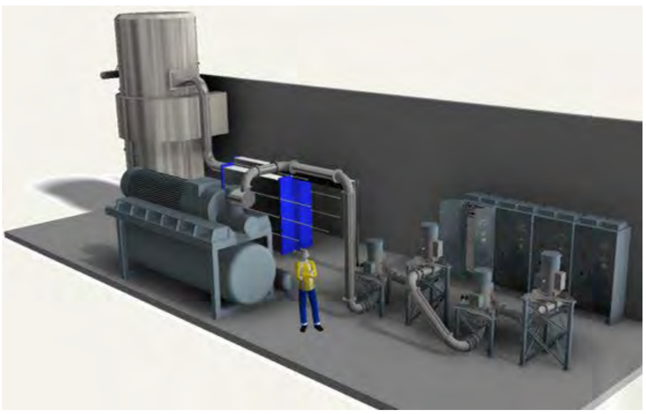

Figure 2: Illustration of SPHP system (Ohmia Industry).

Table 1: Performance.

$T_{source,in}$ [°C]	$T_{source,out}$ [°C]	$T_{sink,latent}$ [°C]	p_{steam} [bara]	$COP_{heating}$* [-]
40	30	120	2.0	2.9
40	30	150	5.0	2.3
60	40	120	2.0	3.6
60	40	150	5.0	2.7
70	50	120	2.0	4.2
70	50	150	5.0	3.0

*The given COP values are indications of the possible onsite performance based on an assumed excess heat recovery temperature and will vary depending on the best suited integration concept.

Project example

Ohmia Industry is currently establishing a showcase for the integrated SPHP system which is supplying 2 tons/h process steam. The heat is hereby extracted from a moist air exhaust, which is cooled down to 30°C while sensible as well as latent heat is recovered. The heat pump is supplying hot water at 80°C and process steam with 2 barA at 120°C. The total energy supply is 1.5 MW and the COP for the steam supplied is 3. Ohmia Industry owns the system and is responsible for the operation. The energy contract includes a guaranteed annual operation to the customer.

FACTS ABOUT THE TECHNOLOGY

Heat supply capacity: 1.2, 2.5 and 5 MW (10 MW optional)

Temperature range: up to 150°C in the form of 5 barA steam supply (latent) as open loop heat pump.

Option for pressurized hot water with temperautre glides in the form of closed loop heat pump.

Working fluid: Ammonia (R717) and Water (R718).

Compressor technology: different compressor technologies for the bottom and top cycle. Centrifugal fan as well as piston compressors.

Specific investment cost for installed system without integration: the system is available with"Energy as a Service" contracts.

TRL level: TRL7-8 (Subsystem are on TRL8-9)

Expected lifetime: 20-25 years (depending on operational hours)

Size: depending on integration and temperature lift

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All information were provided by the supplier without third-party validation. The infomation was provided as an indicative basis and may be different in final installations depending on application specific parameters.

Reversed Stirling Cycle

Olvondo Technology AS

Figure 1: Production of the HighLift high temperature heat pump at Olvondo.

Summary of technology

The configuration of the heat pump is a double-acting alpha Stirling engine of the “Franchot” type. “Double-acting” means, that the working medium is acting on both sides of the pistons. The Franchot type means in contrast to a “Rinia” or “Siemens” type configuration, one of the cylinders is always containing cold gas and one of the cylinders is hot gas.

The driving energy is waste heat with an electrical motor for the piston compressor. The most relevant applications for this technology are food & beverage, process and chemical, pharmaceutical, distilleries, and district heating. Compared to compression and absorption heat pumps, the working medium in a Stirling process is a gas throughout the process. This implies that the process is independent of the evaporation and condensation temperatures of the working medium.

The refrigerant used is R-704 (Helium), which is a natural refrigerant. Helium has both global warming potential (GWP) and ozone depletion potential (ODP) equal to zero and the toxicity and flammability classification of Helium is "A1". The working medium stays a gas throughout the cycle, which makes the heat pump process very suitable for use as very high heat pump’s, while the heat pumps are highly adaptive to any changes in the sink or source temperatures.

Example of the performance of the technology can be seen in table 1.

Table 1: Performance.

$T_{source,in}$ [°C]	$T_{source,out}$ [°C]	$T_{sink,in}$ [°C]	$T_{sink,out}$ [°C]	$COP_{heating}$ [-]
36	34	178	183	1.7
90	85	139	144	2.6
60	55	154	159	2.1
60	55	178	183	1.9

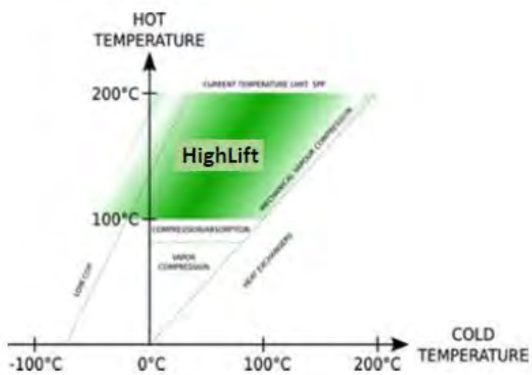

Figure 2: The HighLift high temperature heat pump - recycle low temperature, low value waste heat to high temperature, high value process heat.

The HighLift heat pump can produce steam and cooling in one process, which enables high temperature lifts and delivers very high sink temperatures. The operating range can be seen in figure 2.

Project example

A project example is heat pumps at AstraZeneca, Gothenburg, Sweden. They have historically used fossil fuel for steam production, but have made a conversion from oil to natural gas in 1997. In 2018 a new conversion took palace, this time from fossil natural gas to biogas, to produce steam with a low carbon fuel.

A technical part of the upgrade was to pursue steam production using high lift heat pumps - a more efficient, more robust, less expensive and if possible, even more sustainable solution.

To do this, the site has installed 3 HighLift heat pumps. Each with a capacity of 500 kW_{th} at 10 bar steam system pressure and rejected heat from the chillers for the air condition as a heat source. Another heat pump is scheduled for 2021 with a capacity of 750 kW_{th}.

The pilot installation at AstraZeneca’s R&D center in Sweden aims at increasing the TRL level from 7 to level 9.

FACTS ABOUT THE TECHNOLOGY

Heat supply capacity:
Capacity of 500 kWt_h at 10 bar steam system pressure and rejected heat from the chillers for the air condition as a heat source. Additional heat pump capacity up to 750 kW_{th} is scheduled for 2021.

Temperature range: Heat source: 0 - 100 °C Heat output: 100 – 200 °C.

Working fluid: Helium gas, R-704.

Compressor technology: Piston (double acting).

Specific investment cost for installed system without integration: € 1200 /kW.

TRL level: TRL 9

Expected lifetime: 20 years.

Size: 13 tons and 20 m^2 for each HighLift heat pump

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All information were provided by the supplier without third-party validation. The information was provided as an indicative basis and may be different in final installations depending on application specific parameters.

Compressors and blowers for open loop MVR cycle and steam heat pumps Piller Blowers and Compressors

Figure 1: left: PILLER High Performance Blower, right: Multi-stage system in operation

Summary of technology

In contrast to conventional heat pumps, that use chemical refrigerants, the heat pump solution provided by PILLER uses the existing process fluids, either the vapor from the process or water.
If vapors are compressed directly and then used for heating, the basic principle corresponds to classic mechanical vapor compression (MVR) process (Figure 2).

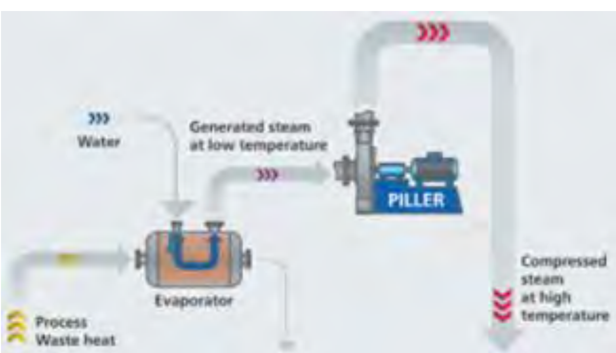

Figure 2: PILLER mechanical vapor compression

In addition to being used for process heating, the compressed vapor can also be used in another process or for the generation of steam or hot water. If it is not a gaseous waste heat stream or if the vapor cannot be compressed, the innovative heat pump cycle with evaporator can be used. PILLER uses water as a working fluid in order to generate steam in the evaporator at a low pressure and temperature (Figure 3).

Figure 3: PILLER steam generation

The High Performance Blowers by PILLER bring the steam to the pressure and temperature to drive the process or heating system needs.
The key element of this Industrial Heat Pump Technology is the compression with the PILLER High Performance Blowers (Figure 1, left). The design of the individual blowers and compressors and their interconnection in a multi-stage system (Figure 1, right) are perfectly adapted to achieve the needed compression of the working fluid. With the retrofitted process, vapor can now be compressed while preserving energy and feeding it at the lowest cost into the processes. A multi-stage system also enables the integration of additional heat sources into intermediate stages. More and more companies are successfully relying on this solution with up to eight stages.

- Driving energy: Electric or by steam turbines
- Most relevant applications: Food and beverages, chemical and petrochemical industry, paper industry.
- Compressor technology: radial turbomachine series of single stages
- Lubrication type: Forced-Oil lubricated bearings, no oil in contact with refrigerant/working fluid/process vapors
- Development status: spinning in field since 1980
- Core components of the machines are highly standardized, solutions and systems are custom engineered. Heat exchangers are specifically sized to the needs (third party production).
- Solutions for large industrial plants with high temperature steam demand or direct vapor recompression for heating column reboilers and evaporators
- Possible combination with low temperature heat pumps for upgrading the first cycles heating duty (condenser) into steam at usable temperature level
- Flexible integration into industrial sites, installation on rigid steal structures above existing equipment
- Outdoor and Installation in hazardous area possible

Table 1: Performance.

$T_{source,in}$ [°C]	$T_{source,out}$ [°C]	$T_{sink,in}$ [°C]	$T_{sink,out}$ [°C]	$COP_{heating}$ [-]
92 (hexane/ water/ vapors)	63.9	80 (Water to steam generator)	126/130 saturated steam on two levels	4.38
94.7 (Flash Vapor)	NA – direct com-pression	94.7 (Flash Vapor)	130.8 saturated steam	7.27
100.3 (Cumene vapors)	86.2	80 (Water to steam generator)	158.5 saturated steam	3.50
53 EtOH/ Water vapors	NA – direct com-pression	100 (Water to steam generator/ Reboiler)	100 saturated steam	4.56

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Project example

EPDM plant: Steam is used for stripping units where solvents from the reaction process are separated from the product. By introducing steam into the stripping unit, a mixed overhead vapor (OHV) containing steam and solvent vapor evaporates. The OHV is then condensed to recover the solvent. Instead of transferring the heat released by condensation into the environment through cooling towers, it is reused to produce low pressure steam in an evaporator. With a multi-stage mechanical vapor recompression (MVR) system, the steam is compressed back to the pressure level that supplies the stripping unit. The Heat Pumping Technology allows integration of additional heat sources between the stages. In this project, flash vapor was fed into the system in the middle of a Steam Compression Cycle. A special evaporator design and the high flexibility of PILLER Blowers guarantee reliable heat recovery, saving over 80 % in energy consumption and reducing CO_2 emissions by 62 % in this single project. In addition to the reduction in steam consumption, the Heat Pump System also reduces cooling water demand, decreasing the overall energy consumption on site. Saving more than 4 Million € annually by retrofitting their existing plants with the Heat Pumping Technology has provided our customer with a payback period of 1.7 years.

FACTS ABOUT THE TECHNOLOGY

Heat supply capacity: > 1MW

Temperature range: 40 – 230°C (212°C saturated steam, 20 barA)

Working fluid: R718 (water), and process vapors (ethanol, methanol, IPA, mixtures, on demand)

Compressor technology: turbo

Specific investment cost for installed system without integration: for > 5MW: 850 €/kW_{th}

TRL level: 8/9

Expected lifetime: 20+ years

Size: Individual (>>1 t, >>10 m²)

Annex 58 High-Temperature Heat Pumps

www.heatpumpingtechnologies.org/annex58/

Qpinch Heat Transformer

Qpinch BV

Figure 1: Several Qpinch Heat Transformer units

Summary of technology

The Qpinch Heat Transformer (QHT) is based on the reversible reaction of phosphate oligomerization inspired by the adenosine triphosphate – adenosine diphosphate (ATP-ADP) cycle in all living cells. This chemical principle is brought to a continuous industrial process in the form of a phosphate *absorption heat transformer*. The system consists of a closed loop phosphate oligomerization and hydrolysis loop, shown schematically in **Figure 2**. The QHT has reached TRL 9 in June 2021 with 3 commercial installations live.

Low temperature residual heat (from industrial processes) drives the whole system. Only ~25 kWh electrical power is used to generate 1 ton of steam. This power is consumed in centrifugal pumps as no compressors are used in this technology.

Applications are found in energy intensive process industry (oil&gas, chemical, metal, food): residual heat, nowadays lost to the environment through air or water cooling, is turned into reusable process heat such as steam, saving CO_2 emissions. Specific applications are the reuse of condensation heat in distillation column overheads as steam to feed the column bottom reboiler, and turning low temperature heat from exothermic reactions into high temperature reusable process heat.

The QHT is flexible in design: the technology can use residual heat from liquid or condensing process streams or a combination thereof. The output, CO_2 neutral process heat, can be in the form of steam, hot thermal oil or hot water.

As the QHT technology is composed of mostly static equipment, operational flexibility is a unique selling point. QHT units can cope with fluctuations in design capacity down to 10% of the initial duty and are able to vary in temperature lift between residual heat source and process heat sink in a safe and automatic way. Concerning start-stop times, from complete shutdown till full-load operation can be achieved within 4 hours, whereas shutdown is just a button push. Additionally, different operational modes can be run so a complete shutdown is often not required and operational continuity is guaranteed.

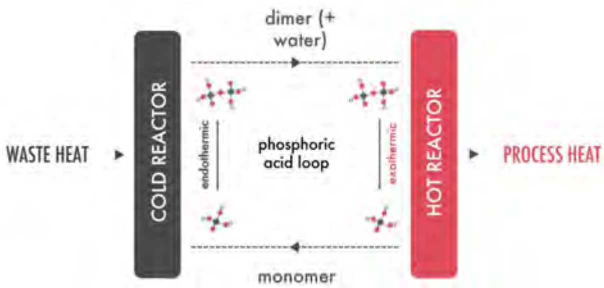

Figure 2: The QHT cycle

The QHT technology does not contain any flammable, explosive, toxic, carcinogenic compounds. It's considered a safe technology both by petrochemical industry as well as food industry. QHT units can be standardized modular skids or completely customized to have the best possible tie-in with a brownfield situation.

For a heat transformer, the coefficient of performance (COP) is defined differently than for electrical heat pumps, hence it cannot be compared. A heat transformer transforms medium temperature waste heat Q_{in} to part high temperature process heat $Q_{out,high}$ and part low temperature waste heat $Q_{out,low}$. COP is then defined as

$$COP_{\text{heat-transformer}} = \frac{Q_{out,high}}{Q_{in}}$$

As heat transformers use no compressors, elecrical power consumption is low, which typically results in low operating costs.

Table 1: Performance

$T_{source,in}$ [°C]	$T_{source,out}$ [°C]	$T_{sink,in}$ [°C]	$T_{sink,out}$ [°C]	$COP_{heat\text{-}transformer}$ [-]
139	124	140	185	0.45
117	106	140	165	0.42
113	110	117	154	0.46

Project example

The goal of the project at Borealis Antwerp was to turn low temperature heat from an exothermic ethylene polymerization reactor and a low pressure steam vent into valuable medium pressure steam (MPS). The project was successful and feedback from the end user was very positive.

To this end, three different residual heat sources were combined via a secondary hot water loop that feeds the QHT unit. This heat is lifted to steam at 3 to 10 bar G. Due to highly fluctuating residual heat production and MPS pressure set point, the designed QHT had to show a lot of flexibility, reliability and ease of operation.

Operational COP values between 0.15 and 0.45 were found. Electrical power consumption was very low, with values around 3-5% of the process heat output.

Possibilities of adjustments and extensions are:

- 3 different residual heat sources are combined into one secondary loop that feeds the QHT. Additional residual heat sources can be coupled to this secondary loop.
- Control software revisions and operational excellence to increase COP is possible.

FACTS ABOUT THE TECHNOLOGY

Heat supply capacity: > 2MW

Temperature range: input waste heat > 80°C, output process heat < 230 °C

Working fluid: water, H_3PO_4 and derivatives

Specific investment cost for installed system without integration: 1 to 2 M€ per MW of process heat production

TRL level: 9

Expected lifetime: 20 years

Size:

2 MW process heat installation: 36 m² footprint, +/- 300 tons weight in standardized steel structure.

10 MW installation: 100 m² footprint, +/- 1000 tons weight.

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All information were provided by the supplier without third-party validation. The infomation was provided as an indicative basis and may be different in final installations depending on application specific parameters.

Rank®

Screw compressor high-temperature heat pump Rank®

Figure 1: Rank® HTHP and compressor

Summary of technology

Rank® is a worldwide recognized company in the design and manufacture of Organic Rankine Cycles for different capacities and applications. Now, Rank® is using this valuable experience in extreme conditions to develop high-temperature heat pumps (HTHP) that can produce renewable heat up to 160 °C.

New Rank® HTHP systems are based on a single-stage cycle with an internal heat exchanger (IHX). However, a two-stage cascade cycle with IHXs can be assembled for covering larger temperature lifts.

The compressor is electrically driven, is based on a screw technology with a frequency inverter to be adapted to the customer's actual operation. The compressor is based on direct drive, avoiding gears or pulleys, minimizing the maintenance, and increasing electrical efficiency. Moreover, magnetic coupling ensures tightness and a-voids the possibility of leakage.

Lubrication used for the proper operation of the compressor is polyolester oil (POE oil) of a specific viscosity, fully compatible with organic working fluids and able to work at high temperatures while keeping the optimum properties.

Rank® HTHP systems can be used in various applications since we have different standard models (HP1 to HP4) adapted to the heat load. Our HTHPs can be designed and sized using our software if they do not suit the applications. The main Rank® HTHP applications include industrial processes (chemical, oil refinery, paper mill, etc.) or district heating.

Our HTHP prototype has been tested at a wide range of heat sink and source temperatures. The measured COP in the lab-scale prototype varied between 2.6 and 6.0, depending on the temperature lift. However, systems specifically designed for clients could reach remarkably higher COPs.

The development status is prototype demonstration (TRL 7), but our commercial department is in discussions for installing our technology in pilot plants for different applications.

Compact HTHP systems are based on plate heat exchanger technology; therefore, the condenser exchanges heat with a thermal oil heat transfer fluid. The evaporator revalorizes heat coming from water or thermal oil. These circuits can be used as intermediary circuits and then be connected to fan coils, among others

Figure 2: Rank® modular solution

Our machines operate through an automatic, efficient managing system without human intervention. Real-time data transmission via the internet allows predictive maintenance by server data analysis, online supervision (PC, mobile phone, tablet, etc.), and remote configuration of working parameters.

Table 1: Performance for the single-stage cycle with IHX HTHP prototype (experimentally measured in lab. prototype, not fully optimized for specific purpose)

$T_{source,in}$ [°C]	$T_{source,out}$ [°C]	$T_{sink,out}$ [°C]	$COP_{heating}$ [-]
84	70	103	5.9
101	70	122	4.6
102	72	130	4.0
115	70	130	3.7
100	90	160	3.0
116	95	160	2.8

Table 2: Case study for production of thermal oil.

$T_{source,in}$ [°C]	$T_{source,out}$ [°C]	$T_{sink,out}$ [°C]	$T_{sink,out}$ [°C]	$COP_{heating}$ [-]
100	70	130	110	3.6
100	80	130	110	4.5

Project example

A perfect application for our HTHP systems is district heating networks (DHN).

DHN are present in urban and industrial environments where each user is connected and uses heat at a given temperature. Heat is distributed at a particular temperature, but users' needs can differ.

HTHPs present in the installations of each client can upgrade the heat at useful levels with a high COP (2.6 to 5.9), adapting the temperature glide of the heat sink.

HTHPs, which local renewable energy sources can power and promote decarbonization in industries connected to district heating networks, independently of the distribution temperature, avoiding the need for fossil fuel boilers.

FACTS ABOUT THE TECHNOLOGY

Heat supply capacity: 120 kW to 2000 kW

Temperature range: useful heat inlet 80 °C to 120 °C and outlet 100 °C to 160 °C / heat source inlet 60 °C to 100 °C and outlet 40 °C to 80 °C

Working fluid: adaptable to the application R245fa, R1336mzz(Z), R1233zd(E)

Compressor technology: Screw

Specific investment cost for installed system without integration: 200-400 € per kW_t, but it varies between temperature levels and applications

TRL level: TRL 7 – prototype demonstration

Expected lifetime: 20 years (with the possibility of hiring Service to extend lifetime and ensure the highest energy performance)

Size: weight 5.5 to 8 tons / surface requried 5.2 to 13 m^2 / height 2.2 to 2.5 m

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All information were provided by the supplier without third-party validation. The infomation was provided as an indicative basis and may be different in final installations depending on application specific parameters.

Industrial Heat Pump

Siemens Energy

Figure 1: Exemplary model of a new Siemens Energy high temperature heat pump

Summary of technology

Siemens Energy heat pumps are specifically tailored for a particular application depending on required capacity, temperatures of sink and source, boundary conditions at site as e.g. electrical connection or available space. A large variety of different cycle designs is possible:

- Closed system in different configurations (with or without flash box, internal heat exchanger, cascade, etc.)
- Compressor drive can be electrical or mechanical (gas engine or gas/steam turbine), both variants within Siemens Energy scope.
- Most relevant applications are chemical, pulp & paper, food & beverage and district heating
- Turbo compressor technology as geared-type or single-shaft depending on application and available space.
- Carnot COPs are in the range of 55 to 70% depending on application (see table 1). COP refers to real outer COP with given temperatures of the actual source and sink media.
- Development status:
  - 50 large scale heat pumps with capacities up to 30 MW and temperatures up to 90 °C built in the 1980s and 90s. Most of them still running today in service of Siemens Energy (fig. 2).
  - Laboratory demonstration of a kW-size heat pump with temperatures up to 160 °C with R1233zd among other tested refrigerants.
  - Pilot plant with 8 MW capacity and 120 °C supply temperature currently being built for Vattenfall in Berlin for a district heating application.
- Source and sink media are preferably water (also steam at sink side). Other media like air or polluted water as heat source can be considered with alternative heat exchanger design or additional measures like ball-cleaning systems.
- Flexible operation and part-load capability is optionally ensured by bypasses, speed-controlled drive and volume flow control (inlet guide vanes).
- Heat exchangers are supplied within scope of Siemens Energy by experienced manufacturers. Plate and shell/tube heat exchangers are possible.

Figure 2: Picture of an existing Siemens energy heat pump

Table 1: Performance.

$T_{source,in}$ [°C]	$T_{source,out}$ [°C]	$T_{sink,in}$ [°C]	$T_{sink,out}$ [°C]	$COP_{heating}$ [-]
2	0.5	43	105*	2.5
35	30	60	120*	2.7
115	105	105	150**	4.1
80	60	20	190***	2.9

*pressurized hot water
**steam
***steam, incl. steam compression

Project example

Pilot plant at Vattenfall in Berlin near Potsdamer Platz for the Berlin district heating network:

- Demonstration of novel high temperature heat pump technology by partners Vattenfall and Siemens Energy supported with subsidies from German government BMWi and PTJ [1]
- Heat recovery of existing turbo chillers at ~30 °C
- Heat supply capacity up to 8 MW for district heating at temperatures from 85 to 120 °C
- Inlet guide vanes, drive speed control and bypasses
- Highly flexible both in thermal power and temperature resulting in high annual utilization

1 https://press.siemens-energy.com/global/de/pressemitteilung/vattenfall-und-siemens-energy-treiben-mit-grosswaermepumpe-die-klimafreundliche

FACTS ABOUT THE TECHNOLOGY

Heat supply capacity:
8 to 70 MW in one unit with one turbo compressor

Temperature range:
Cycle design is tailored based on application. Heat sink up to 160 °C is possible. Large temperature lifts >100 K are possible

Working fluid:
R1233zd(E) and/or R1234ze(E) depending on application (other fluids under development)

Compressor technology:
Turbo (geared-type or single-shaft depending on application)

Specific investment cost for installed system without integration:
250 to 800 €/kW (thermal supply capacity). Depending mainly on capacity, temperature lift and scope

TRL level:
TRL 9 (up to 90 °C); Pilot plant in industrial environment with 120 °C currently built

Expected lifetime: 20-40 years

Footprint: Strongly depending on unit size

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All information were provided by the supplier without third-party validation. The infomation was provided as an indicative basis and may be different in final installations depending on application specific parameters.

SkaleUP

Skala Fabrikk AS

Figure 1: Skala Fabrikk - SkaleUP Cascade HTHP
Picture: SINTEF Energi AS, Christian Schlemminger

Summary of technology

The SkaleUP Cascade HTHP is a unit for a) simultaneous ice and process hot water production or b) utilization and upgrade of low temperature waste heat, i.e. from dry-coolers.

The heat pump is decided as a classical cascade cycle where hydrocarbons are applied to give an optimal performance, while having a high temperature lift of 70 K to 135 K. This high lift enables applications in new designed heating and cooling systems, as well as the retrofit in already existing pressurized process hot water supply systems.

The heat pump is constructed modularly on frames enabling an installation in a 10 feet shipping container or in a machinery room. One module simultaneous provides up to 0.3 $MW_{heating}$ at 115 °C and 0.15$MW_{cooling}$ at 0 °C, process cooling may be realized down to -20 °C with reduced capacity.

The vapor compression cycles with their standardized components, such as semi-hermetic compressors, plate heat exchangers etc. are having service cost and lifetime of classical chillers.

On the heat source side, process ice or chilled water, heat transfer fluid for a dry-cooler circuit or water-based process waste heat streams can be connected. As heat sink a direct implementation in the pressurized process hot water supply system of the plant is favorable. However, heat source and sink side can also be utilize secondary circuits as water/glycol mixtures. A simple process diagram as depicted in Figure 2 indicates the possible implementations. When installing the HTHP in ice water production mode, additional cooling capacity for e.g. production expansion will be available.

The applied natural refrigerants R290 and R600 are classified are nontoxic, having a very low GWP and zero ODP. Working pressures are below 25 bar_a.

Performance data is given in Table 1. COPs were calculated in two ways: for a) simultaneous ice- and process hot water production a combined $COP_{Combined}$ was calculated, taking both heat source and sink into account.

For b) utilization and upgrade of low temperature waste heat the heating $COP_{Heating}$ is considered.

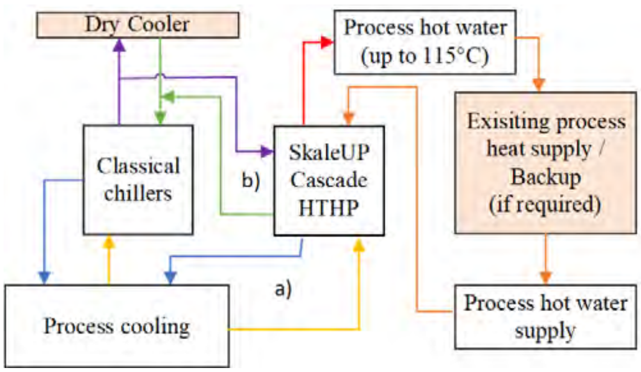

Figure 2: Simplified process diagram of the SkaleUP Cascade HTHP. Connection a) ice water production, b) dry cooler waste heat recovery.

Table 1: Performance estimate, relevant COPs for applications in bolt numbers.

$T_{source, in}$ [°C]	$T_{source, out}$ [°C]	$T_{sink, in}$ [°C]	$T_{sink, out}$ [°C]	T_{lift} [K]	COP heating	COP combined
-15	-20	95	115	135	1.9-2.0	**2.7-2.9**
4	0.5	95	115	115	2.2-2.4	**3.3-3.5**
12	6	95	115	109	2.4-2.6	**3.6-3.8**
25	15	95	115	100	**2.7-2.9**	4.1-4.3

Project example

Simultaneous supply of ice at 0.5 °C water and process hot water at 115 °C as retrofit of a dairy. The SkaleUP HTHP was integrated with a secondary loop water/glycol circuit at heat source side. The ice water return of the dairy was cooled down from 5 °C to 0.5 °C. As heat sink the process hot water return is utilized directly and heated up from 95 °C ±5 K to 110 °C ±5 K. The evaluated $COP_{combined}$, considering heat sink and source side was 3.4 ±0.3. This results in a Carnot-efficiency of the combined heat source and sink of 54 %.

The operation compared to a classical ice water production with NH_3-chillers ($COP_{cooling}$ = 4.5) and process heat supplied by gas burners (efficiency 90 %) indicates a primary energy saving of about 60 %. Using a CO_2-lean energy mix with e.g. 22 gCO_2/kWh_{el} results in a green house gas emission reduction of up to 94 %.

FACTS ABOUT THE TECHNOLOGY

Heat supply capacity: simultaneous up to 0.3 $MW_{heating}$ and 0.15$MW_{cooling}$ per module

Temperature range:
Cycle design tailor made to application, Soruce inlet 25°C to -15°C, Sink outlet 95°C to 115°C, Temperature lift 70 K to 135 K

Working fluid: Natural
R290 (Propane), R600 (n-Butane)

Compressor technology: piston (semihermetic)

Specific investment cost for installed system without integration: 500 €/kW to 700 €/kW thermal supply capacity (sink + source)

TRL level: TRL7 (system prototype demonstration in operational environment)

Expected lifetime: 15 years.

Size: 4.200 kg incl. 10 foot shipping container for 0.3 $MW_{heating}$ at 115 °C and 0.15 $MW_{cooling}$ at 0 °C

Contact information

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All information were provided by the supplier without third-party validation. The infomation was provided as an indicative basis and may be different in final installations depending on application specific parameters.

SPH Sustainable Process Heat

ThermBooster

SPH Sustainable Process Heat GmbH

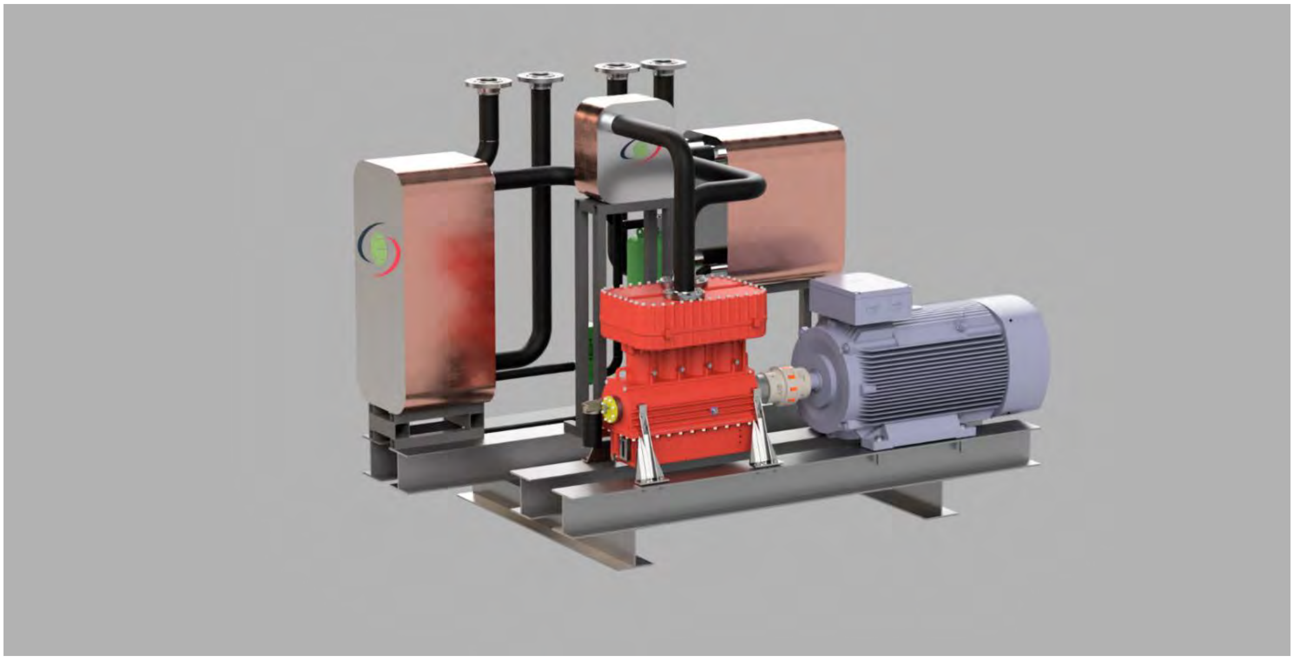

Figure 1: ThermBooster Water-Water configuration.

Summary of technology

The ThermBooster is a closed loop compression type heat pump. It runs with different types of low GWP A1 HFO refrigerants like R1233zd or R1336mzz-Z to reach temperatures up to 165 °C and a thermal power output of about 500-1000 kW per used compressor. The compressor is a 4-cylinder piston compressor, especially designed for the use of HFO in high temperature applications. The piston compressor is an open type with a shaft sealing, driven by an electrical IE4 performance motor. The valve system is optimized for HFO fluids and reduces the pressure losses by up to 30 % compared to standard piston compressors. The compressor has an integrated oil conditioning for heating and cooling of the oil. The used oil type depends on the refrigerant. The hardware itself is designed for temperatures above 250 °C, which can be reached by using natural HCs as working fluid.

The system can be built as water–water or water-steam type. The steam version uses a direct combined condenser/steam evaporator to produce the steam. The system is available as 1-stage system for temperature lifts up to about 60 K and as 2-stage system for lifts up to about 140 K. If starting from low temperature sources, a standard screw compressor is used for the low temperature stage. The stages are coupled by a combined condenser/evaporator heat exchanger. By combining multiple compressors in a parallel configuration higher thermal power output can be reached, also multi-cycle configurations are possible.

The compressor is inverter driven and hence the thermal power can be adjusted very fast in a range between 33 % and 100 %. By choosing a different working fluid and lubricant, the hardware can be adapted to a different temperature level.

The first systems will be deployed into industrial applications in the first half of 2022. The compressor and systems are developed by former Viking Heat Engines Germany developers, with years of experience in the field of piston machines development and ORC/High temperature heat pump systems.

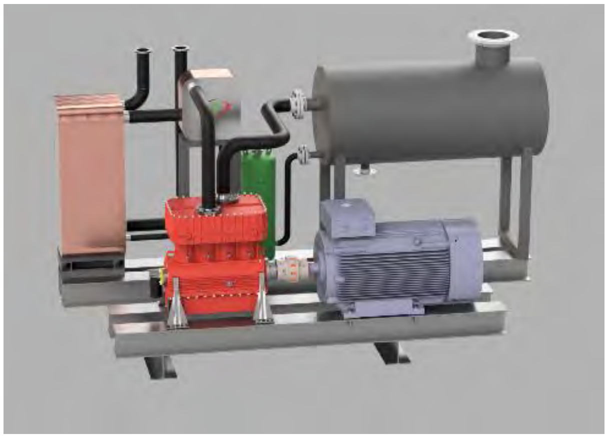

Figure 2: ThermBooster direct steam production.

Table 1: Performance.

$T_{source,in}$ [°C]	$T_{source,out}$ [°C]	$T_{sink,in}$ [°C]	$T_{sink,out}$ [°C]	$COP_{heating}$ [-]
85	78	90	134 (3 bar sat. steam)	3.9 calculated
50	40	90	140 Hot water	2.9 calculated
95	90	95	159 (6 bar sat. steam)	3.0 calculated

Project example

One of the first customer installations will be to produce 2.7 bar saturated steam for a plastic processing company. Target for the company is to reduce the CO_2 foot print of their products. As heat source the cooling water loop of a large CHP engine is used. In this case the ThermBooster is used to cool the CHP engine and uses this low temperature heat to produce steam at the same level as it is done directly with the energy in the exhaust gas. The combination of CHP engine together with the ThermBooster guarantees a use of more than 80% of the total fuel energy of the CHP system, which is prepared for H_2 use in the future to further reduce the CO_2 foot print. The COP in this application is calculated to 3.9 and the payback time is less than 4 years without the consideration of any incentives for investment. The first step will be one CHP in combination with one ThermBooster, after one year the extension to two CHPs, thus reaching a total of three ThermBoosters, is planned.

FACTS ABOUT THE TECHNOLOGY

Heat supply capacity: 300 kW – 5 MW

Temperature range:
Heat source: 20 °C – 120 °C (up to 150 °C planned)
Heat sink: 80 °C to 165 °C (up to above 200 °C planned)
Spread between 5 °C and up to 70 °C or more

Working fluid:
R1234ze, R1233zd, R1224yd, R1336mzz-E, R1336mzz-Z (natural HCs planned for higher temperatures)

Compressor technology: Piston

Specific investment cost for installed system without integration:
150 €/kW for low lift 1-stage systems to 1000 €/kW for high lift 2-stage systems

TRL level:
Former smaller systems TRL 7-8, current larger system TRL 6

Expected lifetime: System service lifetime up to 20 years, compressor lifetime before major overhauling 40,000 – 60,000 h

Size: Single stage, one compressor water-water system 3 x 2 m, 4 tons

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All information were provided by the supplier without third-party validation. The information was provided as an indicative basis and may be different in final installations depending on application specific parameters.

Spilling Steam Compressor

Spilling Technologies GmbH

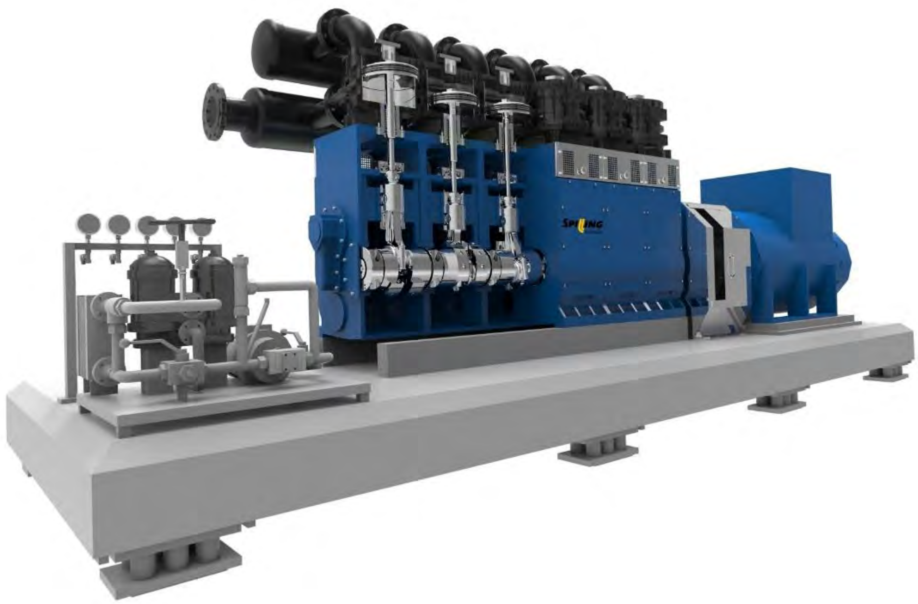

Figure 1: 3D drawing of a Spilling steam compressor.

Summary of technology

Spilling is a known manufacturer of expansion machines and compressors for steam. Historically, the focus has been on steam expanders, which were used to recover power when expanding steam to lower pressure levels. However, in the context of the increasing focus on decarbonization of process heat, the focus shifts to also include steam compressors that are upgrading heat to useful pressure levels and temperatures.

The technology from Spilling is an electric driven steam piston compressor, which can be used both in an open HTHP cycle with steam recycling and a closed HTHP cycle. Typical applications are in the chemical industry, food sector, petro-chemistry, pharma industry, bio-mass processing and other industries.

The design of the compressors is application specific and is based on a modular design with 1 to 6 cylinders, where the piston sizes are adapted for the steam parameters at inlet and outlet, while up to three compression stages can be realized in one unit.

The design is oil-free ensuring no contamination of steam by oil, and the electro-motor includes a variable speed drive for 300 RPM to 1,000 RPM, and accordingly a steam flow variation from approximately 30 % to 100 %, which provides high efficiency, also in part load, and gives good regulation behavior, also for fast changing loads.

The technology is most promising for temperatures and pressures above 120 °C at 2 bar(a) for the source side, and 250 °C and 40 bar(a) for the sink side. The pressure increase of each stage is possible up to a factor of 3 per compression stage, hence with a triple stage compressor a temperature increase of >100 K is possible in the same unit. For lower source temperatures than ~120 °C, a combination with steam blowers or other closed heat pumps is possible.

The compressor portfolio covers steam flows between approx. 2 t/h to 20 t/h and thermal loads between approx. 1 MW to 15 MW.

About 20 compressor units with this technology have been sold in the last 20 years.

Table 1 shows the estimated performance for the technology for various temperature ranges.

Table 1: Estimated performance for steam compression in open cycles.

$T_{source,in}$ = T_{evap}	$T_{sink,out}$ = T_{cond}	$COP_{heating}$*
[°C]	[°C]	[-]
125	151	9.5
133	230	3.5
148	175	10.3
152	211	5.3
175	215	8.4

* Ratio of condensing heat (with subcooling to 105 °C) to compression power.

Project Example

An example of an application is recycling of excess steam from reactor cooling at a chemical plant located in North England. In this application a Spilling steam compressor is installed with two units in parallel:

- 1 x 6-cylinder compressor (double stage)
- 1 x 3-cylinder-compressor (double stage)

The inlet pressure/temperature is 5 bar(a) at 152 °C, and the outlet pressure/temperature is 19.5 bar(a) at 211 °C with a COP of 5.3 at a steam flow rate on the suction side of (11 + 5.5) t/h = 16.5 t/h and a heat load of the HP steam at the discharge side at ~(8 + 4) MW = 12 MW (for the two units).

The recycling of excess steam is here a much better option than production of electricity with the excess steam (by means of a steam turbine) from both an energy efficiency and economical point of view.

FACTS ABOUT THE TECHNOLOGY

Heat supply capacity: 1 MW to 15 MW

Temperature range: Source >120 °C; sink < 250 °C (typical) resp. < 280 °C (max). Temperature lift of up to 100 K in one unit (three stage compressor) possible

Working fluid: R-718 (water)

Compressor technology: Piston compressor

Specific investment cost for system without integration: 100-400 €/kW

TRL level: TRL 9

Expected lifetime: ~20 years

Size: ~15 tons to 45 tons and ~35 m² to 70 m² (size of installation room)

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All information has been provided by the supplier without third-party validation. The information was provided as an indicative basis and may be different in final installations depending on application-specific parameters.

Screw compressor for water vapor heat pump technology

Svenska Rotor Maskiner International AB

Figure 1: SRM prototype compressor skid

Summary of technology

SRM is currently developing a steam screw compressor for applications in process industries. A protype has been tested in the laboratory, while the full-scale system is under development and planned for full-scale demonstration in 2023/2024.

The steam screw compressor from SRM is a positive displacement compressor which was designed for steam system use. It is electrically direct driven by a frequency-controlled motor. Lubrication is provided by a separate oil skid in order to feed the bearings with oil. Sealing of the water steam against oil is performed by advanced labyrinth shaft seals. The system can be operated in open cycles, e.g. working between two steam distribution systems, or in a closed cycle.

For testing the prototype, the compressor was integrated with a closed cycle heat pump system and operated in a short period in the test laboratory. The heat pump system was heated and cooled by external water/glycol system for the test purpose.

The purpose of the prototype system was to demonstrate the application of a screw compressor in a heat pump system intended for large steam systems in paper and pulp industry as well as other energy intensive industries. The prototype system delivered heat to a stream being heated from 119 °C to 126 °C, while cooling a stream from 90 °C to 86 °C. The condenser heat power was measured to 230 kW during this test, corresponding to a COP of 1.9. However, there were considerable losses from the compressor oil system and compensating these losses in full scale operation is expected to yield a COP of up to 2.7.

As a next step, the full-scale system is being developed with a nominal capacity of 2 MW at an evaporating temperature of 100 °C. The compressor is planned with a volume flow rate of 6000 m^3/h and can operate at evaporation temperatures between 75 °C and 120 °C with a maximum pressure ratio of 10. This corresponds to condensing temperatures of up to 140 °C (for T_e = 75 °C). An overview of the expected performance in a closed cycle arrangement is shown in Table 1.

Table 1: Expected performance for full scale system

$T_{source,in}$ [°C]	$T_{source,out}$ [°C]	$T_{sink,in}$ [°C]	$T_{sink,out}$ [°C]	$COP_{heating}$ [-]	$\dot{Q}_{heating}$ [kW]
91	90	139	140	4.7	1360
101	100	139	140	6.9	1980
111	110	139	140	10.5	2820
91	90	159	160	1.9	1000
101	100	159	160	2.6	1310
111	110	159	160	3.8	2130

The development and demonstration of the full-scale unit will be conducted in collaboration with DTI, MultiKøl og Energi, Verdo and a number of Danish partners and end-users between 2022 and 2025.

Project example

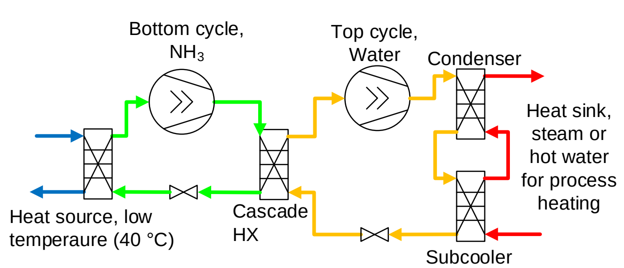

Figure 2: Flow sheet of R-717 and R-718 cascade system.

The system is most promising for applications in which heat is to be upgraded from above 90 °C. As many applications require heat to be upgraded from lower temperatures, it is likely to be applied in a cascade arrangement with an ammonia system. A typical application could be heat recovery from industrial excess heat to hot water or steam production. For these applications, there is a considerable potential, since it can replace boilers in an existing utility system with a minimum of required retrofitting. A possible system layout is shown in Figure 2. For this system, a COP of approximately 4.0 is expected.

FACTS ABOUT THE TECHNOLOGY

Heat supply capacity: Prototype: 250 kW, next model: 2 MW

Temperature range: 80 – 130 °C (prototype). Next model up to 165 °C

Working fluid: R-718 (water)

Compressor technology: Screw

Specific investment cost for installed system without integration: -

TRL level: 5, full-scale field demonstration expected for 2023/2024

Expected lifetime: 20 years

Size: compressor skid: 2.5 tonnes including frame and oil system. Footprint: 6 m^2

Contact information

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All information were provided by the supplier without third-party validation. The information was provided as an indicative basis and may be different in final installations depending on application specific parameters.

TC-C920

ToCircle Industries

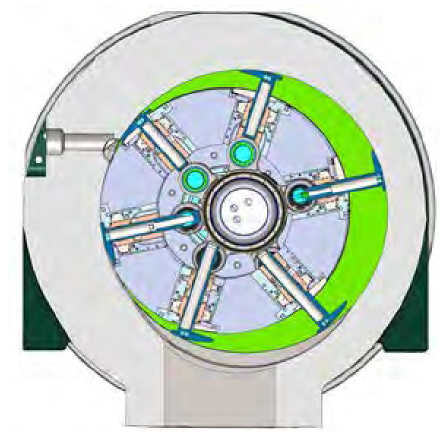

Figure 1: Cross-sectional area of TC-C920 compressor

Summary of technology

Tocircle's technology is a rotary vane compressor (TC-C920) which can be used both in open loop heat pump (Mechanical Vapor Recompression) or closed loop heat pump operating with pure steam or a binary mixture of steam and ammonia as the refrigerant. The compressor is a positive displacement machine driven by an electrical motor.

The compression chambers are formed between the static outer casing and the vanes connected to the rotor (see figure 1). Unlike in conventional rotary vane compressors, the extension of vane tips in Tocircle's compressor is controlled with bearing technology mounted in the machine center. This results in no friction between the casing and vane tips, and hence no need for oil lubrication in the compression chambers.

The rotary vane compressor has a highly flexible operational range, and it is not limited with regards to minimum flow (surge) and maximum flow (stonewall/choke), The compressor is highly tolerant to liquid. Erosion and water hammers are not problematic. There are no limitations for the transport media on the heat sink and heat source side.

The most relevant applications for this compressor technology are in the following industries: Food & Dairy, Aquaculture, Petrochemical and Metal industry.

Internal lubrication is achieved through liquid injection into the internal bearings in the compressor, resulting in two-phase evaporative compression of the refrigerant. The discharged compressor flow is at the saturation temperature. The external bearings (drive end and non-drive end main bearings) are lubricated with a circulating oil. The oil is in a separate system, and it is sealed off from the process.

The technology is currently being tested in a full-scale pump heat pump pilot at Tocircle's test facility in Norway. The next step is a pilot operated at industrial site. The performance for the in-house pilot is given in **Table 1**.

Table 1: Performance

$T_{source,in}$	$T_{source,out}$	$T_{sink,in}$	$T_{sink,out}$	$COP_{heating}$ [-]
112°C	112°C	141°C	141°C	5.41

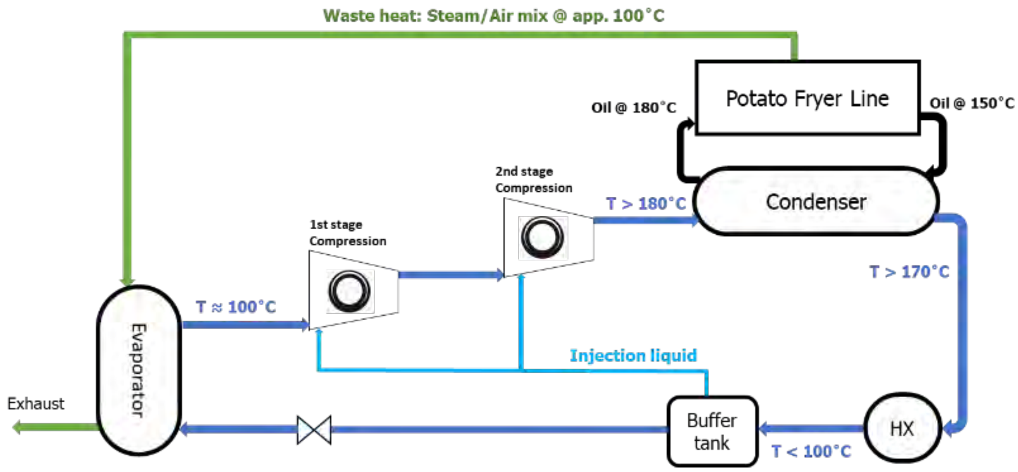

Figure 2: Potato frying line – heat pump flow chart

Project concept:
Tocircle and the Duynie group have formed a long-term partnership to develop a high-temperature heat pump for french fries frying lines. The heat pump will upgrade low-temperature waste heat from the frying line to high-temperature thermal energy to heat the vegetable oil in the line.

Tocircle will deliver the compressor package in a closed loop heat pump. The heat source is a mixture of steam and hot air at ca. 100°C. This is upgraded to above 180°C in two compression stages. The refrigerant is a binary mixture of water and ammonia. The pilot heat pump has a thermal capacity of 1.5MW and the full-scale heat pump a thermal capacity of 5 MW. The heat pump COP is expected to be in the range 4-5.

Contact information

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FACTS ABOUT THE TECHNOLOGY

Heat supply capacity: 1-5 MW

Temperature range: Maximum temperature lift is approx. 90˚C, maximum condensation temperature in the heat sink is 188˚C.

Working fluid: Water (R718) and ammonia (R717). The working fluid can be either pure water or a binary water/ammonia mixture.

Compressor technology: Rotary vane compressor

Specific investment cost for installed system without integration: 250-430 €/kW (depending on heat pump size). The costs specified are for the compressor package only and not the complete heat pump system.

TRL level: 6-7

Expected lifetime: 20 years

Size: A compressor package with 2 compressors has a footprint of 3.0m x 2.5m.

All information were provided by the supplier without third-party validation. The infomation was provided as an indicative basis and may be different in final installations depending on application specific parameters.

Turboden Large Heat Pumps

Turboden S.p.A

Figure 1: Illustration of LHP.

Summary of technology

Large Heat Pumps (LHP) are utility-scale heating plants that allow to transfer large quantities of heat from a colder source to a higher temperature heat user.
Turboden LHP technology – based on closed cycle - takes advantage of 40+ years' experience with custom made products operated by means of high temperature thermodynamic cycles.
Turboden's LHP systems are designed application specific, selecting the proper cycle layout, working fluid and designing the main components based on the specific project need. LHP technology summary:

- Highly efficient: Electrically driven system based on turbo compressor technology.
- Large scale: Thermal power output from 3 MW_{th} to 30 MW_{th} per single unit.
- High lift: Up to more than 100 °C, possible thanks to custom design.
- High temperature: Output up to 200 °C with the possibility to generate steam.
- Environment-friendly: Experience with 10+ different working fluids with low GWP and low ODP.
- Main application: Large scale heat user with required temperature up to 200 °C with possibility to generate steam – mainly district heating network (DHN) and industrial user with possibility to generate steam.
- Base solution with:
    - Heat source side: Liquid form heat carrier. Possibility to evaluate different streams such as process mixture, etc.
    - Heat user: Heat carriers could be either liquid (water, thermal oil, etc.) or vapour (saturated steam, superheated steam, etc.)

Additional information:

- Application specific design.
- Possible combination with storage system (not part of Turboden scope of supply).
- Heat exchangers are typically shell & tube type with the possibility to select proper materials depending on the specific application.
- Flexible operation and with fast start-up and shut down.

Table 1: Estimated performance for selected conditions

$T_{source,in}$	$T_{source,out}$	$T_{sink,in}$	$T_{sink,out}$	$COP_{heating}$
[°C]	[°C]	[°C]	[°C]	[-]
15	8	60	90 (hot water)	2.75
95	80	90	150 (sat. steam)	3.1

Project example – HEATLEAP project

The HEATLEAP project aims to demonstrate the environmental and economic benefits of waste heat recovery systems in energy intensive industries by testing these technologies at real scale. The project is partially funded under the LIFE program (EU's funding instrument for the environment and climate action).

The ultimate goals of this project are the valorization of waste heat streams from the cooling of the steelmaking process can be upgraded through a large-scale heat pump and used for district heating instead of being wasted, i.e. dissipated through cooling towers.

Here below the main technical features of LHP:

- LHP size: 6 MW_{th} design heat output.
- Operative temperature: Design case 95°C with possibility to have output temperatures up to 120 °C.
- Flexibility: LHP output temperature adjustable depending on district heating network needs (requiring a variable temperature between 85 °C and 120 °C).
- Full integration with DH network. Control system designed to be highly flexible depending on DH network operating temperature.
- High flexibility with 2 compression stages and variable frequency driver (due to a very variable process)

FACTS ABOUT THE TECHNOLOGY

Heat supply capacity: 3 MW to 30 MW per single unit

Temperature range: Up to 200 °C or 12 bar steam, with maximum lift exceeding 100 °C

Working fluid: Turboden already experienced with more than 10 different fluid between refrigerants, hydrocarbons and siloxanes.

Compressor technology: Turbo compressor

Specific investment cost for installed system without integration: 700 - 300 €/kW (thermal supply capacity) depending on the LHP unit size and temperature

TRL level: 7 – 9

Expected lifetime: 20+ years

Size: Custom made - depending on specific size and application

- High speed centrifugal compressor
- Working fluid: Low GWP HFO, R1233ZD

Table 2: Design case performance in HEATLEAP

$T_{source,in}$	$T_{source,out}$	$T_{sink,in}$	$T_{sink,out}$	$COP_{heating}$
[°C]	[°C]	[°C]	[°C]	[-]
75	70	65	95	8.2

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All information were provided by the supplier without third-party validation. The infomation was provided as an indicative basis and may be different in final installations depending on application specific parameters.

WS. Turbo Steam
Weel & Sandvig ENERGY AND PROCESS INNOVATION

Weel & Sandvig
ENERGY AND PROCESS INNOVATION

Weel & Sandvig

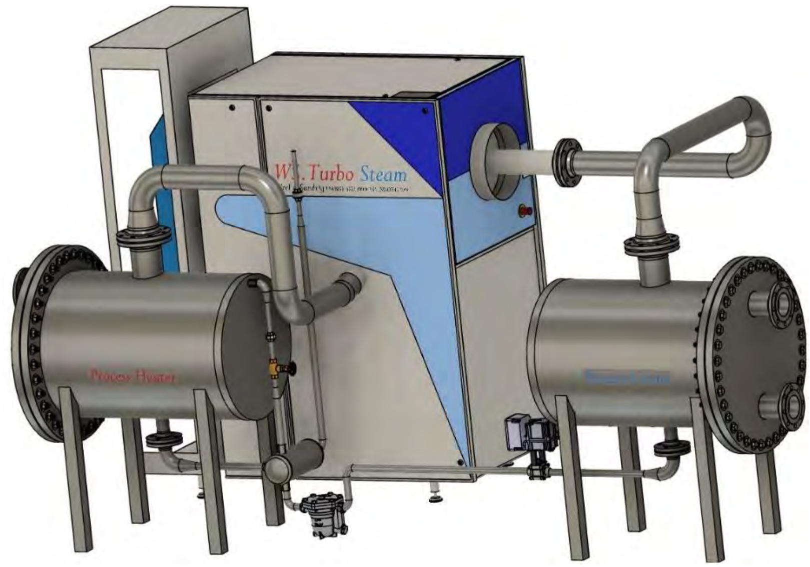

Figure 1: WS Turbo Steam: Here as a one stage direct drive turbo compressor working on steam (R718) in a closed loop process heat pump system with condenser "Process Heater" and evaporator "Process Cooler".

Summary of technology

- Turbo compressor operating in steam (R718) either as open system (direct on process steam/water) or as a closed water/steam loop and process heat exchangers (see **Figure 1**).
- The system as 1-stage or cascaded in multi-stages.
- Compressor is driven directly by a 100 kW high speed (70 krpm) PM electric motor.
- Most relevant applications are upgrading excess heat sources with temperatures from 80 -110 ˚C with temperature lift of 20 - 25 ˚C as 1-stage and up to 55 ˚C as 2-stage application.
- COP: Typically COP will be between 5 and 13 depending on required temperature lift.
- Technology consists of high efficient advanced 3D centrifugal compressor and high speed drive.
- Lubrication: Ceramic bearings are oil lubricated with an external oil loop. There are no contact between steam and lubricating oil system.
- Performance: Examples (see **Table 1**) of COP for one and two stage operating are based on compressor map (measured in air and conversion to steam).
- Development status: Weel and Sandvig is in the phase of laboratory demonstration (own test rig) at Technical University of Denmark (see **Figure *2***).
- Process heat exchangers will be specified according to process media, etc.
- Systems will be based on a few standard compressor units with various trim on impellers.
- Startup time: From hot system approximately 5 minutes.

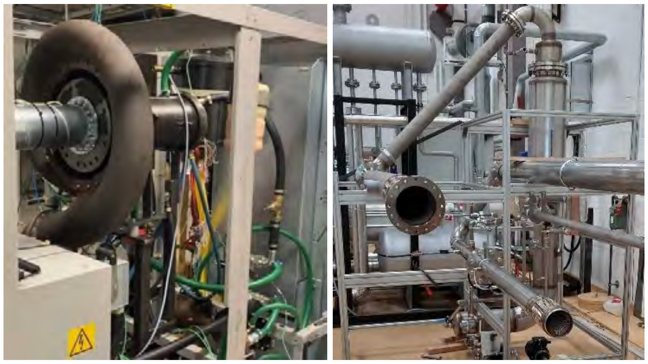

Figure 2: Left: Turbo compressor and high speed motor. Right: Steam test rig before compressor installation.

Table 1: Performance.

$T_{source,in}$	$T_{source,out}$	$T_{sink,in}$	$T_{sink,out}$	$COP_{heating}$
[°C]	[°C]	[°C]	[°C]	[-]
100	99	120	120	10.0
100	99	150	150	5.0

Example: Efficient electrification of drying in superheated steam

Combustion of fuel for heat supply in drying (with related emission of green house gases) can be eliminated by converting e.g. a tunnel dryer to use superheated steam (instead of hot air) in combination with a heat pump.

- In this case the dryer now operates with steam heated to an inlet temperature of 145 °C and a steam exit temperature of 110 °C. Demand for reheating recirculated steam is 1080 kW.
- With a two-stage steam turbo compressor heat in excess steam from dryer exit can be extracted to be used for reheating the recirculated steam to 145 °C. Electric power demand to compressors is 200 kW corresponding to a COP of 5.3.
- Simple payback is estimated to approximately 3 years assuming annual operation of 5000 hours, specific cost of heat and electricity of 38 €/MWh and 60 €/MWh, respectively.

FACTS ABOUT THE TECHNOLOGY

Heat supply capacity: 1 MW to 5 MW

Temperature range: Maximum supply (sink) temperatures 145 –160 ˚C. Temperature lift 20 ˚C (one stage) and up to 55 ˚C. Source temperature 80 ˚C – 110 ˚C.

Working fluid: Water (R718).

Compressor technology: Turbo.

Specific investment cost for installed system without integration: 150 - 250 €/kW heat supply.

TRL level: From TRL 4 (Technology validated in lab) to TRL 9 (Actual system proven in operation).

Expected lifetime: 20 years.

Size of 100 kW power unit: Compressor with motor: Weight: 100 kg, footprint 0.5 m^2

Compressor module incl. frequency drive: Weight 700 kg, footprint 2 m^2.

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