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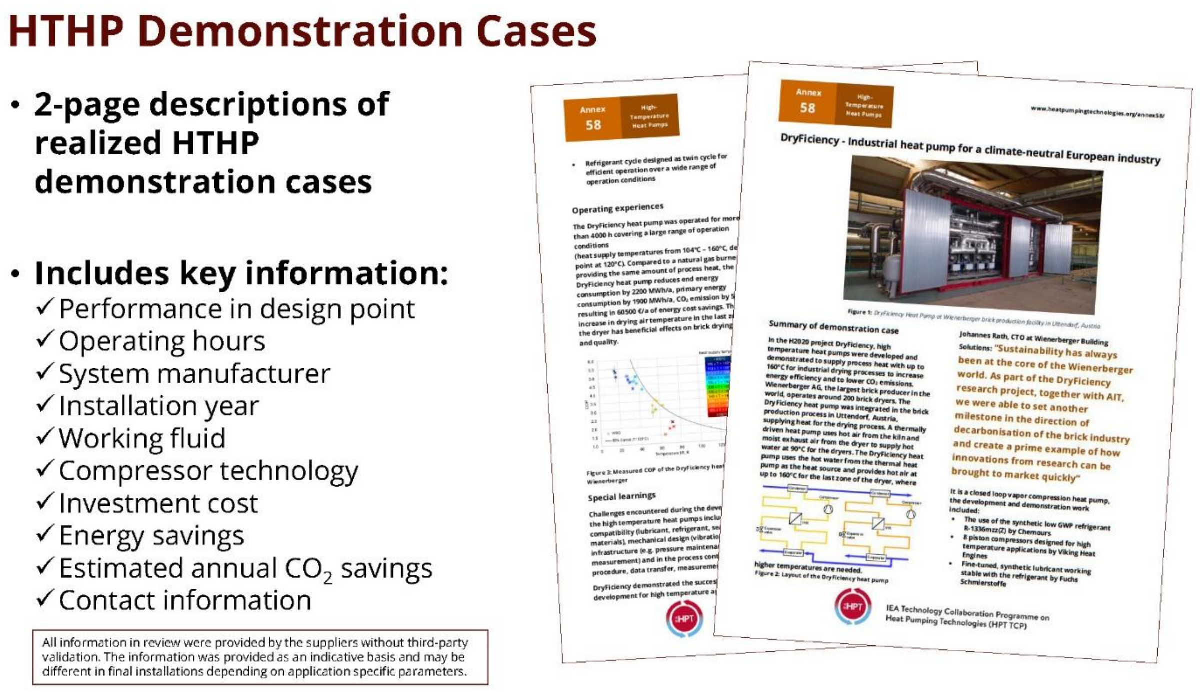
Final report from 12 October 2022

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

Appendix 3

Factsheets HTHP Demonstration Cases



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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.

Factsheets
High-Temperature Heat Pump Demonstration Cases
IEA HPT Annex 58

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4. MHI Thermal Systems 130C hot water supply heat pump for drying process at Takaoka Toko
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7. Qpinch Reducing CO2 and plant OPEX with Qpinch Heat Transformer at Borealis
8. SINTEF Open loop MVR steam heat pump dryer Scanship waste management DryFiciency project
9. SkaleUP HTHP for Simultaneous Process Cooling and Heating
10. Spilling Steam compressor for recycling of excess steam at chemical plant in the UK
11. Spilling Steam compressor for steam recycling at pulp drying
12. Wienerberger DryFiciency Industrial heat pump for a climate-neutral European industry

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

High temperature heat pumps demonstrated in energy intensive industries

Figure 1: *DryFiciency Heat Pump at AGRANA Starch production facility in Pischelsdorf, Austria*

Summary of demonstration case

In the H2020 project DryFiciency, high temperature heat pumps were developed and demonstrated to supply process heat with up to 160°C for industrial drying processes to increase energy efficiency and to lower CO_2 emissions. AGRANA is a global player in the segments of fruit, starch and sugar, specializing in the processing and refinement of high-quality agricultural raw materials. The DryFiciency heat pump was integrated in the wheat starch dryer, it uses warm water from a heat recovery cycle as the heat source and supplies approx. 10% of the heat demand of the dryer.

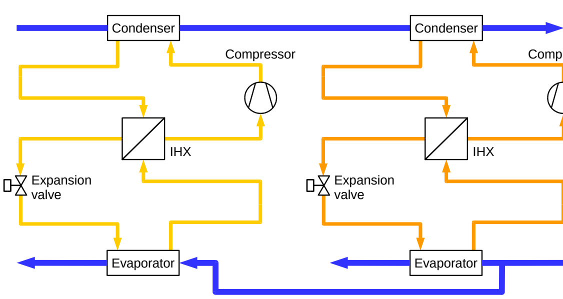

Figure 2: Layout of the DryFiciency heat pump

Norbert Harringer, CTO and Member of the Management Board of AGRANA Group:

"AGRANA is committed to CO2-neutral production. It is clear that this requires an action plan with ambitious but realistic milestones. Specifically, this means that AGRANA will invest around EUR 10 million annually through 2025 to save 25% of the greenhouse gas emissions caused by our production and to reduce them to net zero by 2040. The DryFiciency project is also a building block in our climate strategy for achieving our emissions targets."

It is a closed loop vapor compression heat pump, the development and demonstration work included:

- The use of the synthetic low GWP refrigerant R-1336mzz(Z) by Chemours
- Innovative screw compressors designed by BITZER adapted to high heat supply temperatures
- Fine-tuned, synthetic lubricant working stable with the refrigerant by Fuchs Schmierstoffe
- Refrigerant cycle designed as twin cycle for efficient operation over a wide range of operation conditions

Operating experiences

The DryFiciency heat pump was operated for more than 4000 h with a maximum heat output of 374 kW (design point at 138°C heat supply temperature). Compared to a natural gas burner providing the same amount of process heat, the DryFiciency heat pump reduces end energy consumption by 2400 MWh/a, primary energy consumption by 1700 MWh/a, CO_2 emission by 660 t/a, resulting in 42900 €/a energy cost savings. The internal heat recovery cycle is an efficient heat source allowing for valorisation of waste heat from other processes at the site.

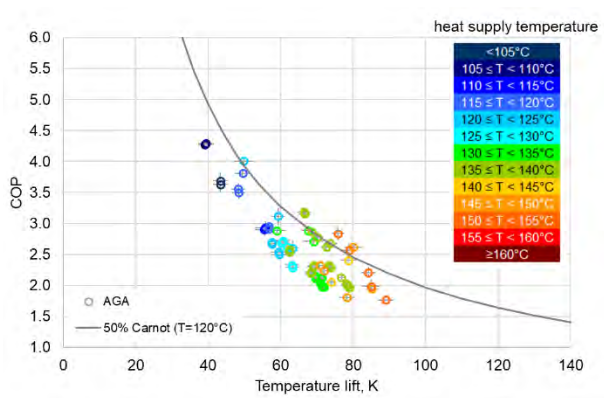

Figure 2: Measured COP of the DryFiciency heat pump at AGRANA

Special learnings

Challenges encountered during the development of the high temperature heat pumps included material compatibility (lubricant, refrigerant, sealing materials), mechanical design (vibrations), integration infrastructure (e.g. pressure maintenance, flow measurement) and in the process control (e.g. start up procedure, data transfer, measurement devices). DryFiciency demonstrated the successful component development for high temperature applications such as compressors, lubricant and refrigerant as well as the successful operation of the closed loop heat pumps in industrial environment.

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

FACTS ABOUT THE CASE

Installation year: 2020

Operating hours: over 4000 hours

Working fluid used: HFO-1336mzz(Z)

Compressor technology: screw compressors

System manufacturer: built by AMT Kältetechnik based on the design by AIT

Performance in design point:

- Heat source: 76°C → 72°C, water
- Heat sink: 96°C → 138°C, water
- Heat supply capacity: 374 kW
- $COP_{Heating}$: 3.2

Performance at 152°C heat supply temperature

- Heat source: 81°C → 78°C, water
- Heat sink: 102°C → 152°C, water
- Heat supply capacity: 340 kW
- $COP_{Heating}$: 2.87

Investment cost pilot installation: -

Savings: 42900 €/a at 138°C

Estimated annual CO_2 savings: 660 t/a at 138°C

Mechanical vapor recompression for drying process at Hadano water treatment center

Figure 1: Heat pump-based sewage sludge drying system

Summary of demonstration case

At small and medium-sized sewage treatment plants, sludge generated in the sewage treatment process is mechanically dehydrated. The dehydrated sludge is carried out and disposed of. This industrial waste disposal cost is a heavy burden.

On the other hand, sewage sludge is expected to be used as a stable and large amount of biomass resource. For its utilization, sludge drying process is necessary. However, it is difficult to introduce conventional drying equipment, which requires a high cost, at small and medium-sized sewage treatment plants.

Hadano water treatment center has the similar challenges. In cooperation with Okawara Mfg. Co., Ltd. and Kansai Electric Power Co., Inc., they addressed the demonstration project using heat pump for the purpose of reducing drying cost as one of B-DASH (Breakthrough by Dynamic Approach in Sewage High Technology) projects. The demonstration project has been conducted as a government-commissioned research from NILIM (National Institute for Land and Infrastructure Management).

At this water treatment center, sludge of 9,360 t/a is generated. The average water content of the sludge is 72%W.B. (wet base). By the newly developed drying system, the sludge is dried to less than 20%W.B.

The newly developed drying system is composed of an indirect dryer and a mechanical vapor recompression system (Figure 2). In the dryer, sludge is heated by conductive heat transfer with the tubes in which steam flows. The dryer acts as a condenser. The drain from the dryer is decompressed with an expansion valve. The low-pressure wet steam is heated in an evaporator which recovers heat from exhaust gas. The dry steam is compressed with a roots blower and a screw compressor (by KOBELCO). The first-stage blower compresses the

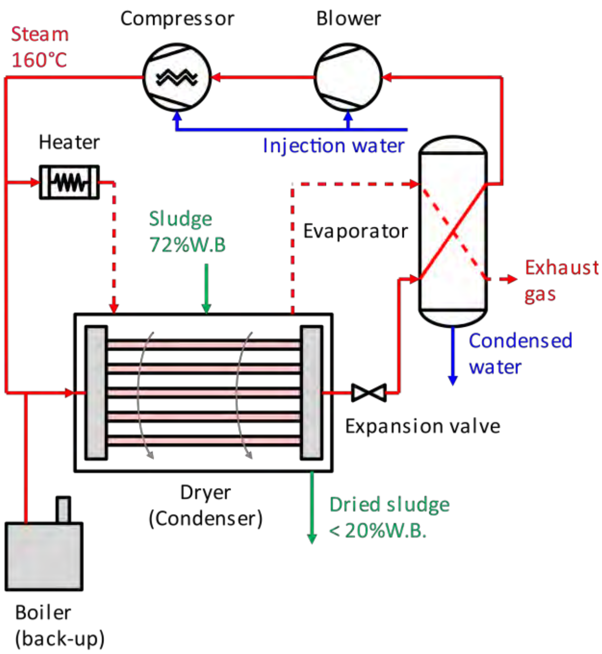

Figure 2: System configuration

steam to atmospheric pressure level, and then the second screw compressor compresses the steam to 0.5MPaG (160°C).

A part of the 160°C steam is superheated by an electric heater and is used for the carrier gas. A back-up boiler is also equipped and used in the case of the system start-up or the steam shortage.

Operating experiences

The drying system can reduce the life cycle cost by 22% compared to the case of outsourcing the waste disposal. On the other hand, compared to the case of drying the sludge with a conventional hot air rotary dryer, the newly developed drying system can reduce the life cycle cost, energy consumption and CO_2 emissions by 40%, 46% and 51%, respectively.

Special learnings

For the end-user, the decisive factors in the installation of the heat pump-based drying system were the followings:

- Reduction of total running costs (Reduction of industrial waste disposal cost exceeds additional electricity cost.)
- Easy operation and maintenance because of electricity system

FACTS ABOUT THE CASE

Intallation year: 2016

Working fluid used: R718 (water)

Compressor technology: Roots blower (Anlet) + Twin-screw compressor (KOBELCO)

System manufacturer: Hadano city office, Okawara Mfg. Co., Ltd. and Kansai Eectric Power Co., Inc.

Performance in design point:

- **Heat source:** 93°C (0.078 MPa, steam)
- **Heat sink:** 160°C (0.6 MPa, steam)
- **Heat supply capacity:** 675 kW
- **$COP_{Heating}$:** 2.9

Link to webpage:
https://www.jeh-center.org/asset/00032/monodukurinidenki/vol6_hadanocity.pdf

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Steam supply heat pump for distillation process at Hokkaido Bioethanol

Figure 1: Steam supply heat pumps

Summary of demonstration case

Bioethanol is a renewable and alternative fuel made by fermenting and distilling biological resources such as wheat, corn, sugar beet and rice. Hokkaido bioethanol CO., Ltd. was established in 2007 as a pilot project by the Ministry of Agriculture, Forestry and Fisheries for model community using biofuel. It manufactures dehydrated ethanol with a concentration higher than 99.5% from the raw materials such as beet syrup or non-standard wheat and rice by grinding, liquefying, fermenting, distilling and dehydrating. During the bioethanol production, a lot of steam is used for heating. Steam consumption of distillation process accounts for about 60% in the total processes. Hence it is important to improve the energy efficiency of the distillation process.

In the distillation process, steam is used to heat the ethanol aqueous solution (10% ethanol and 90% water) and to separate the ethanol and water through evaporation. Evaporated ethanol is cooled and liquified in the distillate cooler. The liquid (95% ethanol and 5% water) is taken to the dehydration process with zeolite membrane, and then pure ethanol (more than 99.5%) is produced.

In the conventional system of the distillation process, steam for heating was supplied by heavy oil-fired boiler, and condensation heat from ethanol was wasted through cooling tower. For the purpose of heat recovery from the condenser and steam supply to the distillation column, steam supply heat pump (SGH120 by KOBELCO) was installed in 2013.

In the new system, the waste heat is recovered as a heat source water of heat pump. The heat pump lifts the heat at 65°C and produces steam at 110–120°C. 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 is supplied to the distillation column, This amount accounts for 70% of the total steam demand. The remained 30% is covered with the existing boiler.

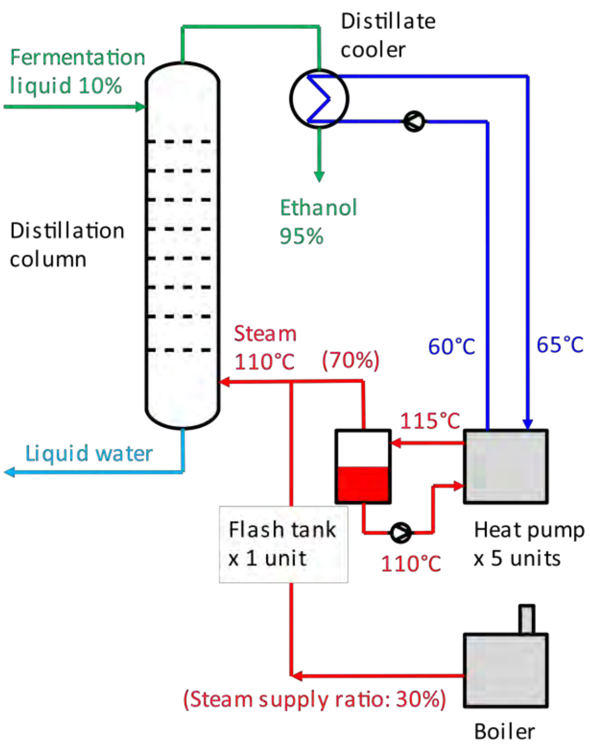

Figure 2: System configuration

FACTS ABOUT THE CASE

Intallation year: 2012

Working fluid used: R245fa

Compressor technology: Twin-screw

System manufacturer: KOBELCO

Performance in design point:

- **Heat source:** 65°C → 60°C (water)
- **Heat sink:** 20°C (water) → 120°C (steam)
- **Heat supply capacity:** 370 kW/unit
- **$COP_{Heating}$:** 3.5

Link to webpage:
https://www.jeh-center.org/asset/00032/monodukurinidenki/vol4_hokkaidobaioetanoru.pdf.pdf

Operating experiences

The heat pump can operate at the COP of more than 4 thanks to the lower steam supply temperature than designed. Compared to the conventional system, CO_2 emissions and energy cost can be decreased by 43% and 54%, respectively. It was confirmed that the investment cost of the heat pump equipment can be recovered in about 3 years.

Special learnings

The end-user was concerned about the reliability of this heat pump before the operation because this was the first case this heat pump was installed in an actual plant. However, the heat pump operates without problems, and he is pleased with the good performance as planned.

"The distillation process requires stable temperature control. Obviously, this was the suitable process for a waste heat recovery and steam supply system using heat pump, because waste heat is stably obtained," says the end-user.

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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.

130°C Hot water supply heat pump for drying process at Takaoka Toko

Figure 1: Hot water supply heat pump

Summary of demonstration case

Oyama factory of Takaoka Toko produces mainly electric transformers for distribution at 6 kV. 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. If the drying is not sufficient, the paper and the copper wire do not adhere well. Hence the drying process is one of important processes affecting the product quality.

Conventionally, boiler steam was used in the drying process of the transformer coil. Despite the purpose of removing water from the coil, the iron core was also heated at the same time. This increased the drying time. It was a significant problem that a lot of time and heat were consumed.

A diagnostic survey of energy usage in the drying process was started in 2008 to realize both of saving time and reducing energy consumption. As the result, the following measures were taken:

- Reviewed the manufacturing process and changed the drying process for the coil alone
- Introduced a heat recovery high-temperature heat pump alternative for existing steam boiler

In the previous system, steam boiler was used for producing hot air. And the exhaust gas from the dryer had relatively high temperature, but not recovered. Likewise, in another process (annealing process), there was waste heat.

In the new system, a heat pump (ETW-S by MHI Thermal Systems) 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.

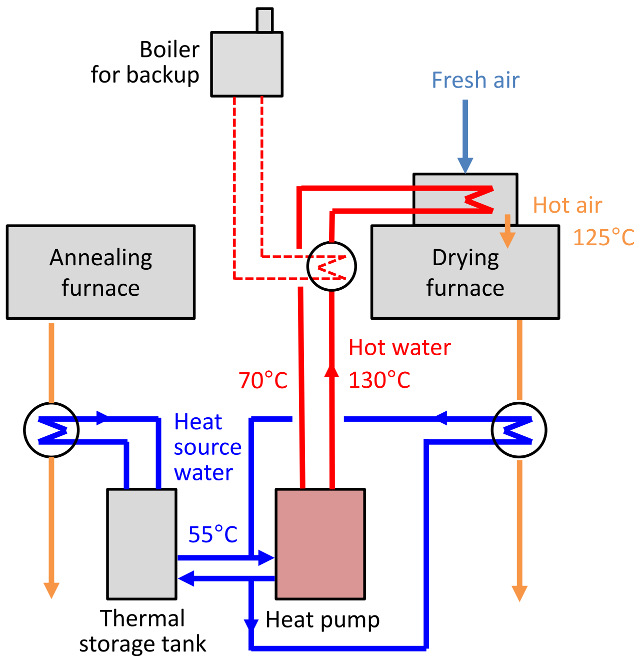

Figure 2: System configuration

FACTS ABOUT THE CASE

Intallation year: 2012

Working fluid used: R134a

Compressor technology: Centrifugal

System manufacturer: MHI Thermal Systems

Performance in design point:

- **Heat source:** 55°C → 50°C (water)
- **Heat sink:** 70°C → 130°C (pressurized water)
- **Heat supply capacity:** 627 kW
- **$COP_{Heating}$:** 3.0

Link to webpage:
https://www.jeh-center.org/asset/00032/monodukurinidenki/vol3_toukoutakaoka_oyama.pdf

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.

Operating experiences

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. In addition, by changing the drying process for the coil alone, the drying time has been significantly reduced, and the production lead time has been reduced from 5 days to 2 days.

Special learnings

Preliminary detailed analysis of the heat demand and waste heat before the installation of the heat pump was the key to success. Especially, the exhaust gas properties and its effect on the heat exchanger were analyzed as well as measuring the amount of heat from the exhaust gas.

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High Temperature Heat Pump for Steam Production at AstraZeneca

Figure 1: Two of the three heat pumps currently installed at AstraZeneca's R&D facility in Gothenburg, Sweden. Heat is transferred to the heat pump from the heat recovery circuit and steam is delivered from the heat pumps' steam generators to the steam distribution system. The third heat pump is installed on the opposite side of the room.

Summary of demonstration case

AstraZeneca (Gothenburg, Sweden) has historically used fossil fuel for steam production. An upgrade from oil to natural gas was made in 1997, and another upgrade was made to biogas in 2018, which have resulted in reduced CO_2 emissions over the years.

A technical part of the upgrade was to pursue steam production using high temperature heat pumps - a more efficient, more robust, less expensive and if possible (depends on source of electricity), even more sustainable solution.

To do this, the site has installed 3 HighLift heat pumps from Olvondo Technology. Each with a capacity of 500 kW heat at 10 bar steam system pressure, and with rejected heat from the chillers for the air condition as a heat source. A fourth heat pump which is an upgraded version with a capacity of 750 kW heat, is scheduled for installation in Q2 2021.

Main components of the installations in addition to the heat pumps are the cold circuits, the hot circuits and the steam generators.

The cold heat source is a heat recovery circuit that is transferred indirectly to the heat pumps. The heat pumps use this heat to heat a hot circuit that circulates over a steam generator. The steam generator uses this heat to generate steam that is fed to the steam distribution circuit of the plant.

The cold circuits are closed water circuits that transfer heat from the heat recovery system at the site to the heat pumps. The hot circuits are closed, pressurized water circuits that transfer heat from the heat pump to the steam generators. The steam generators are shell and plate heat exchangers that gets feed water from the site's feed water tanks and generate steam by cooling the hot circuit from the heat pump. The generated steam is thus supplied directly to the steam distribution system at the site.

Operating experiences

The heat pumps have been running between 5000 hours and 6800 hours. The running time for each pump has been:

- Heat pump #1: 6800 hours
- Heat pump #2: 5000 hours
- Heat pump #3: 6500 hours

The load has been varying, but the temperatures have remained quite constant during operation.

Special learnings

A proven concept for a Stirling engine operated as an industrial-scale heat pump is made in this demonstration case, where steam is delivered at 180 °C.

A brief assessment of losses and benefits is given, followed by technical performance data on the current installation at AstraZeneca's R&D center in Sweden.

Current activities involve improving system efficiency and reliability while increasing the heat output from 500 to 750 kW, and at the same time raising the TRL of the heat pump from level 7 to level 9.

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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.

FACTS ABOUT THE CASE

Intallation year: 2017

Operating hours: 6100 hours acummulated on average for the three heat pumps since installation.

Working fluid used: R-704 (Helium)

Compressor technology: Piston

System manufacturer: Olvondo Technology AS

Performance in design point:

- Heat source: 36 °C → 34 °C (water)
- Heat sink: 178 °C → 183 °C (steam)
- Heat supply capacity: 1.5 MW
- $COP_{Heating}$: 1.7

Investment cost: 3xHighLift heat pumps approximately 1,800,000 € (excluding internal integration, but including monitering & control system and Helium solution.

Savings: Energy savings 9.4 GWh yearly

Estimated annual CO_2 savings: 600 t/a

Link to webpages;
highlift.olvondotech.no

https://klimat2030.se/astrazeneca-i-goteborg-leder-fossilfri-utveckling/

Optimizing EPDM Plants: Waste heat recovery in thermal separation processes through steam generation using MVR Blower Technology

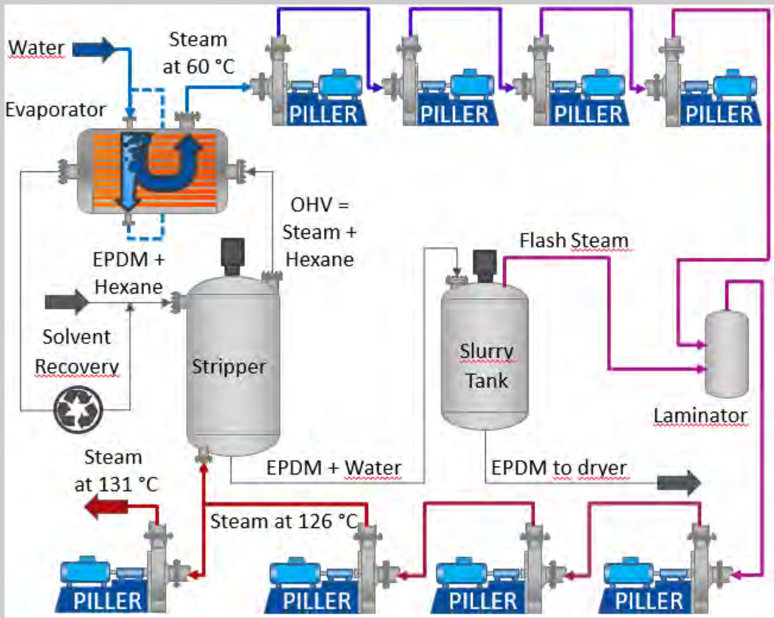

Figure 1: SSBR Strippers, EPDM Plants, Flash Vapor Recovery and Cumene Columns – all these chemical and petrochemical processes were optimized with state-of-the-art PILLER MVR Blowers. Benefitting from Heat Pump Systems based on MVR Blower Technology not only means reducing operational costs, CO2 emissions also are significantly reduced using a waste heat recycling process.

Summary of demonstration case

As the expert in design and manufacture of customized, efficient, and high-performance blowers, PILLER offers unique solutions for every project. After analyzing and rating potential savings for customers in a feasibility study, individual heat pump systems are engineered to optimize CO2 and energy savings. We started with a recovery rate of 6.5 tons per hour, eventually reaching 31.7 tons (usable) steam per hour.

In the case of an EPDM Plant, a steam generating Industrial Heat Pump was built in 2017.
Steam generation here 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.

"Together with our customers, we are striving for reduced greenhouse gas emissions – implementing industrial heat pump systems based on MVR blower technology."
Dr. Steffen Kuberczyk, Global Sales Director of Piller Blowers & Compressors

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 Industrial 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 the Steam Compression Cycle.

Operating experiences

A special evaporator design and the high flexibility of PILLER Blowers guarantee reliable heat recovery, saving over 80 % in energy consumption and reducing CO2 emissions by 62 % in this single retrofitting 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 plant with the Industrial Heat Pump solution by PILLER has provided our customer with a payback period of 1.7 years.

With more than a dozen installations, PILLER established its position as the pioneer for large scale steam generating heat pumps.

FACTS ABOUT THE CASE

Intallation year: 2017

Operating hours: ~8000 hours/a

Working fluid used: R718 (water)

Compressor technology: Turbo

System manufacturer: Piller Blowers & Compressors

Performance in design point:

- **Heat source:** 92°C n-Hexane, Water → 60 °C Water
- **Heat sink:** 126 °C / 131 °C reintroduced for process heating
- **Heat supply capacity:** 10 MW
- **$COP_{Heating}$:** 4,4

Investment cost: 6,800,000 €

Savings: 4,000,000 €/a

Estimated annual CO_2 savings: 12,400 t/a

Link to webpage or report:

https://www.piller.de/fileadmin/media/pdf-files/product-sheets/steam-regeneration-epdm.pdf

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PILLER Blowers & Compressors

Reducing CO_2 and plant OPEX with Qpinch Heat Transformer

Figure 1: Heat transformer unit based on revolutionary Qpinch technology: commercial unit in Antwerp to demonstrate capabilities of technology as well as scale-up potential for wider Borealis operations and technologies

Summary of demonstration case

The Qpinch Heat Transformer (QHT) transforms low temperature heat from an exothermic ethylene polymerization reactor and a low-pressure steam vent into valuable medium and high pressure steam (MPS & HPS). This is a unique technology that functions as a heat transformer and therefore only requires 3-5% of the thermal output power as electricity. This is wildly different from standard heat pump technology where electricity consumption is far greater. On top, the QHT is able to generate temperature lifts of residual heat close to 80 degrees. This lifts waste heat above the plant's pinch point, turning waste heat into valuable steam at no OPEX.

The unit operates by using three different residual heat sources that are combined via an intermediate hot water loop that feeds the QHT unit. This heat is lifted to steam at 3 to 10 bar g. The LDPE reactor produces over 40 different recipes and therefore emits highly fluctuating residual heat temperatures and output. Therefore, the QHT has to show a lot of flexibility, reliability and ease of operation in order to

"This collaboration points to the enormous potential of open innovation between like-minded technology pioneers. We are confident that this project will be the first of many successes built on co-operation with Qpinch. For Borealis, the start-up of this unit is a landmark achievement in our mission to re-invent for more sustainable living."
Erik Van Praet, Borealis Vice President Innovation and Technology

harvest all available residual heat and produce stable MPS or HPS, ranging from 400 kW to 1.3 MW. The unit is installed as an add-on on the current reactor setup with minimal integration efforts. The QHT can re-value close to 50% of the waste heat that is offered to the unit. This brings value to Borealis in 3 ways. One, there is a significant direct energy cost saving on MPS and HPS since Qpinch produces this without Opex. Two, the CO_2 emissions of the site directly declines since the steam boilers need to produce less MPS and HPS and at last, Borealis shows that it knows how to act in a changing environment and is a leader in sustainable innovation in a conservative industry.

The QHT unit is installed at the Zwijndrecht site of Borealis with a footprint of 4 x 6 metres and a height of 15 metres. The unit can easily be switched on and off without causing any harm to reactor operations. **Figure 2** schematically shows the working principle of the QHT, while **Figure 3** shows its integration at Borealis.

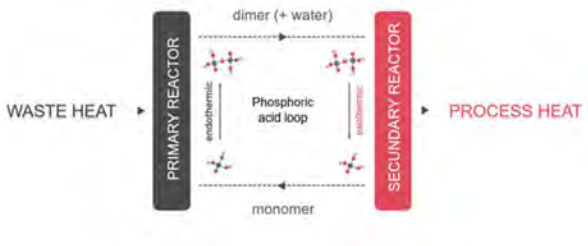

Figure 2: Schematic overview of the waste heat transformer. Oligomerization of phosphoric acid in transforming waste heat into covalent bond chemical energy. This energy is released upon reversing the reaction in the secondary reactor.

Operating experiences

Borealis has known a production increase thanks to free and carbon neutral steam from the QHT unit, and this without requiring expensive electrical infrastructure to drive the heat recovery. Furthermore, a cooling debottlenecking by 50 % net reduction on specific cooling demand was achieved.

Special learnings

Per installed MW, the QHT can produce 1.7 ton/h carbon neutral medium pressure steam. Each year, this avoids ~2,000 ton CO2 emissions (~1,500 ICE cars) and saves 190,000 € EU ETS credits.

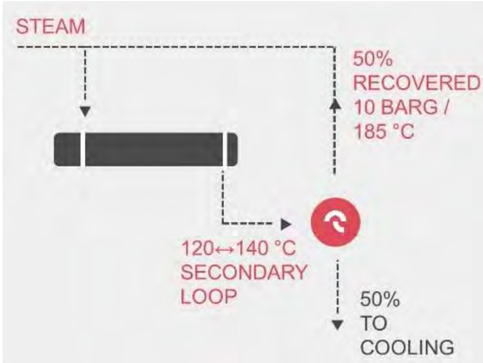

Figure 3: Integration of the QHT at Borealis, the values for a single operating point are given

FACTS ABOUT THE CASE

Intallation year: 2020

Operating hours: 2500 hours

Working fluid used: phosphoric acid (H_3PO_4)

Compressor technology: n/a, heat-driven heat transformer

System manufacturer: Qpinch

Performance in design point:

- **Heat source:** 80°C to 135°C, water and steam
- **Heat sink:** 140°C to 185°C, saturated steam
- **Heat supply capacity:** 2.9 MW
- **$COP_{heat\text{-}transformer}$:** up to 0.45 (for a heat transformer, COP is defined as the ratio of process heat to waste heat, see **Figure 2**)

Estimated annual CO_2 savings: 2,200 t/a

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.

Open-loop MVR steam heat pump dryer – Scanship Waste management / DryFiciency project

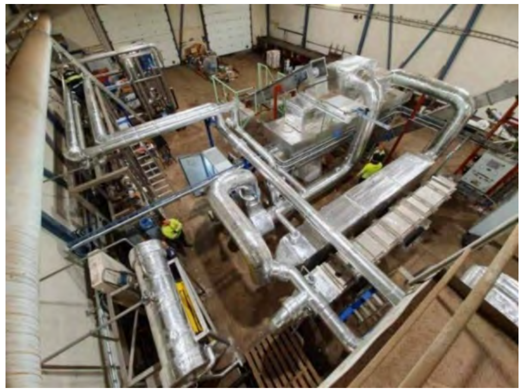

Figure 1: From the demonstration site at Scanship, Drammen, (Dryficiency.eu, 2020).

Summary of demonstration case

In the Dryficiency project a two-stage turbo-compressor steam heat pump system has been installed at Scanship's test site in Drammen. Scanship is a Norwegian based company, which produces advanced waste-water purification and management systems for the marine industry. The heat pump is integrated with an innovative dryer, which can be used for to dry bio-slugde, wood chips, garden compost etc.

The heat pump demonstrator is an open loop Mechanical Vapor Recompression (MVR) system. The heat pump, developed by the DryFiciency consortium uses advanced, low-cost turbo-compressor technology originating from the automotive sector. The demonstrator, as seen in Figure 2 aims to reduce the dryer's energy demand by up to 75% and eliminate the dryer to operate based on fossil fuels.

The turbo-compressors themselves are developed by Rotrex, a Danish technology SME., The rig is developed by Epcon Evaporation Technology and SINTEF. The working fluid is water, a natural refrigerant, which is a non-toxic, non-explosive, reliable and available in abundance. The compressors operate oil-free in two stages. The impeller design is customized for each stage. The rotational speed for the impellers is up to 90 000 rpm, which is enabled through a DC-motor via a planetary gearbox, which is oil cooled.

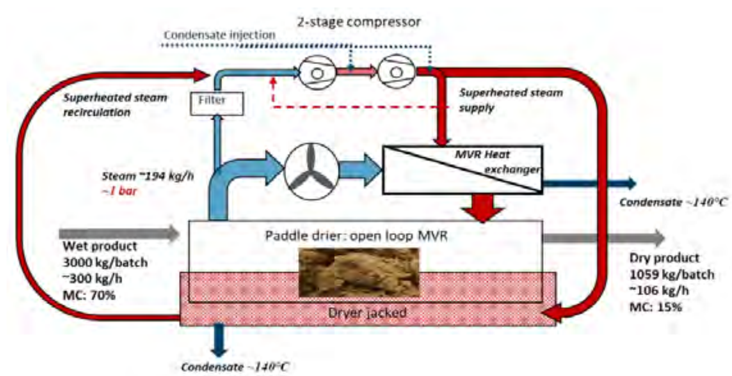

Figure 2: Schematic integration layout of MVR-dryer for sludge drying (Schneeberger et al., 2021).

To reduce the temperature prior to the next compressor stage a de-superheating system is installed. This is done by direct water injection, which is sprayed into heat pump after 1st and 2nd stage. The added water is precisely controlled to avoid sub-cooling and droplet formation inside the compressors.

The steam heat pump stages compress surplus steam coming directly from the dryer from ambient (100°C, 1 bara) up to pressures of 4.2 bara, giving a pressure ratio per compressor stage up to 2.1. The demonstrated isentropic efficiency of the turbo-compressors are between 0.7-0.8. The saturated steam from the compressor rig then supplies heat to the steam to be used in the dryer via an MVR heat exchanger. The condensate holds around 140°C and can potentially be used for other heating purposes.

The demonstrator has achieved a capacity of 500 kW_{th}, and utilizes up to 1 ton steam per hour, while the heat pump rig has sufficient capacity to support two driers.

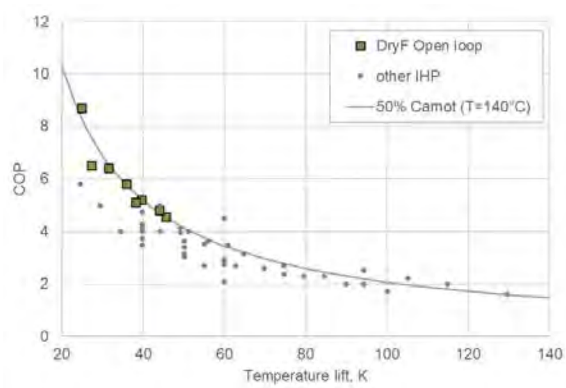

Figure 3: Performance of the DryF test-rig (Wilk, V., et al 2022)

The rig was tested at various operating conditions, ranging from supply temperatures from 125°C – 146°C. Good performance was achieved with COP-values from 4.5 up to 8.7, (Carnot efficiencies of around 50%) depending on the temperature lift, see Figure 3.

Operating experiences

Through operation a fully functional drying system was validated with 2-5 bar steam pressure delivered, drying 50 tons of garden waste during site acceptance tests. The open loop heat pump was able to deliver at least 4.5 bar.

There were some operational start-up challenges to integrate the turbo-compressor heat pump with the steam dryer in terms of maintaining superheated steam coming from the dryer, which in turn reduced the capacity of the heat pump.

FACTS ABOUT THE CASE

Intallation year: 2020

Operating hours: N/A

Working fluid used: Water

Compressor technology: Turbo-compressor

System manufacturer: Rotrex, Epcon Evaporation Technology, Scanship

Performance in design point:

- **Heat source:** 100°C steam
- **Heat sink:** 125-146°C steam
- **Heat supply capacity:** 500 KW_{th}
- **$COP_{Heating}$:** From on-site testing: 4.5 (T_supply: 146°C, 8.7 (T_supply: 125°C). Both with T_source: 100°C

Investment cost: N/A

Savings: Energy costs reduced by approximately 82%

Estimated annual CO_2 savings: N/A, (primary energy consumption reduced by 76%)

Link to webpage or report:

(DryFiciency.eu, 2022): https://dryficiency.eu/demonstrations/scanship-waste-management/

(Schneeberger et al., 2020) – Schneeberger, A., Helminger, F., Bantle, M., 2021 DryFiciency D4.3 – "Integrated Heat Pump Systems"

(Wilk et al., 2022) – Wilk, V., Bantle, M., Schneeberger, A., 2022 DryFiciency - D5.4 – "Final report on the heat pump technologies developed"

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HTHP for Simultaneous Process Cooling and Heating - SkaleUP

Figure 1: SkaleUP cascade HTHP installed in 10 feet container, Trondheim Norway
Picture: SINTEF Energi AS, Christian Schlemminger

Summary of demonstration case

The SkaleUP Cascade HTHP is a unit developed for a) simultaneous ice- and process hot water production or b) utilization and upgrade of low temperature waste heat, i.e. from dry-cooler circuits. The HTHP is placed in a 10 feet shipping container serving as a machinery room, having ventilation and gas detection. SkaleUP is integrated as a retrofit for existing boilers at a dairy of TINE SA located in Trondheim Norway. Here, both operation modes are under validation.

The dairy is producing about 75 million liter milk products per annum. It´s process cold and heat supply is simplified depicted in Figure 2. The process cold is supplied by NH_3-chillers 80%, a CO_2 heat pump 10% and the SkaleUP cascade HTHP 10%. Process heat is supplied by electric boiler 90% and the HTHP 10%. Fresh water heating, mainly used for cleaning in place (CIP), is covered by the CO_2 heat pump working in transcritical operation. District heating and oil-fired boilers are serving as backup for the heat supply.

The SkaleUP cascade HTHP uses natural working fluids and it´s design comprised of:

- Classical cascade cycle with direct cascade heat exchanger and internal heat exchangers
- Working fluids low-temperature cycle R290, high-temperature cycle R600
- Heat source: a) ice water 5°C → 0,5°C, secondary water/glycol circuit 3 °C → -1 °C supplies heat to R290 evaporator, b) Water/glycol from existing dry cooler circuit 20°C → 12°C, secondary water/glycol circuit 18 °C → 10 °C supplies heat to R290 evaporator
- Heat sink side direct exchange to pressurized process hot water 95 °C → 115°C, 300kW$_{th}$

The HTHP development started in 2015 under the umbrella of the HeatUP-project (Grand NFR-243679) and HighEFF (Centre for Environment-friendly Energy Research, 257632/E20) analyzing the needs of sustainable heat supply different industrial processes and developing a laboratory scale HTHP system with 30 kW$_{th}$ condenser capacity lifting form 0 °C to 115 °C. In 2019 the project consortium (Skala Fabrikk AS, TINE SA, Cadio AS and Officine Mario Dorin S.p.A and SINTEF) teamed up supported by The Research Council of Norway (Grand NFR-296374) to develop an industrial HTHP system and demonstrate the technology at a dairy of TINE SA.

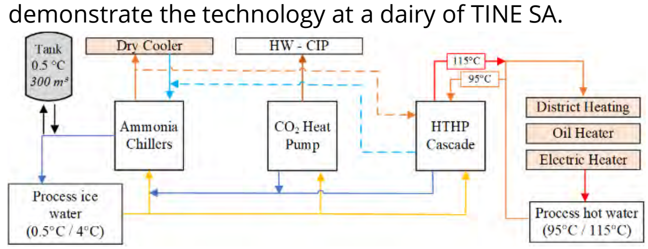

Figure 2: Simplified integration of the SkaleUP cascade HTHP

Operating experiences

The analysis carried out during full operation of the dairy and covers the ice water operation mode. The load profiles of the process heat and cold indicate a simultaneous demand, with peak shift of up to two hours.

Peak loads are 1.6 MW_{th} process heat and 1 MW_{th} cold. Minimum demand is in both cases about 200 kW_{th}. The $COP_{combined}$, where both heat sink and heat source are considered, is the best KPI for heat source and sink utilization with small temperature glides with less than 30 K. A comparison of the $COP_{combined}$ and $COP_{heating}$ is depicted over the temperature lift in Figure 3. Thus, the $COP_{heating}$ is used to predict the operation using the dry cooler circuit as heat source.

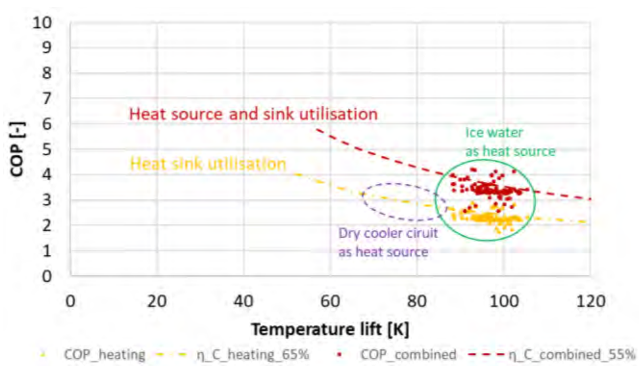

Figure 3: Performance of SkaleUP cascade HTHP

For a 100 K temperature lift the COP combined is in the order of 3.4, giving a Carnot-efficiency of 54%. The COP heating is about 2.3 at the same conditions resulting in a Carnot-efficiency of 65%. The analysis conducted allows a projection of the low temperature waste heat utilization from, i.e. dry coolers to a $COP_{heating}$ in the range of 2.5 to 3.3 for a temperature lift in the range of 85 K to 70 K.

Considering a typical production week, where all the thermal process heat of 117 MWh_{th} is supplied with the SkaleUP cascade and operation of the transcritical CO_2 heat pump results in a remaining ice water cooling demand of 5.9MWh_{th}. Considering a $COP_{cooling}$ of 4.5 for the remaining ice water production, results in a reduced primary energy consumption from 126 kWh to 58 kWh or 53%. Secondary effects, of the HTHP integration is the reduced peak load of the electric grid compared to electric boilers as well as reduction of CO_2 emissions of up to 94 %, compared with a natural gas based heat supply.

Special learnings

A continuous work on the HTHP topic and the awareness of the potential allowed the end-user to tune the production process i.e. reducing the supply temperature in the existing dairy. Further, reduction potential can be utilized by designing new processes and plants optimized for HTHP integration, as conducted in the dairy TINE Bergen, Norway.

FACTS ABOUT THE CASE

Intallation year: 2021

Operating hours: 6500 hours/a

Working fluid used: R290, R600

Compressor technology: piston (semihermetic),

System manufacturer: Skala Fabrikk AS

Performance in design point:

- **Heat source:**
  - Ice water mode 5 °C → 0 °C, water
  - Waste heat mode i.e. 20 °C → 12 °C, water/glycole
- **Heat sink:** 95 °C → 115 °C, pressurized water
- **Heat supply capacity:** 0.3 MW_{heat} + 0.15 MW_{coold}
- **COP:** (Measured at seconday side close to HTHP)
  - Ice water mode 3.4 ±0.3, T_{lift} 95K ±10K
  - Dry cooler mode estimated 2.5 to 3.2

Investment cost: 500 €/kW to 700 €/kW thermal supply capacity (sink + source)

Savings: up to 62% primary energy

Estimated annual CO_2 savings: up to 94 %

Link to webpage or report: Schlemminger et al.: HTHP mit natürlichen Kältemitteln, DKV-Tagung 2021 Dresden, Germany

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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.

Steam compressor for recycling of excess steam at chemical plant in the United Kingdom

Figure 1: One of the two steam compressors installed at chemical plant, United Kingdom.

Summary of demonstration case

At a chemical plant in North England, a completely new production line was installed, where excess steam from a reactor cooling is available with 5 bar(a). The first idea was to use it to generate some electricity by means of a steam turbine. But because of the low available pressure, only quite low electrical efficiency would have been resulting. Reconsidering the situation, the idea was born to instead recycle the complete heat content in the steam by compressing it to 19.5 bar(a), where it could be used again as process steam for other applications. For this purpose Spilling piston steam compressors were chosen. This type of compressor is characterized by good efficiencies and high flexibility, since they are operated with variable speed, enabling a variation from ~30 to 100 % steam flow rate.

For the given application, the compression from 5 to 19.5 bar(a) takes place in two stages. In a first stage from 5 to ~12 bar(a), and in a second stage then from ~12 to 19.5 bar(a). During compression the steam also becomes superheated, hence it is released on the discharge side at ~240 °C.

The Spilling steam compressor is a modular system with up 6 cylinders. For the full available excess steam flow rate of 16.5 t/h, two units were required like follows: a 6-cylinder unit (with four low pressure (LP) cylinders and two high pressure (HP) cylinders) with a capacity of 11 t/h, and a 3-cylinder unit (with two LP cylinders and one HP cylinder) with 5.5 t/h capacity. Before each compression stage, a certain quantity of condensate is injected into the steam, to avoid too high steam temperatures from the compression. By this, the steam flow rate on discharge side of the both units increases from 16.5 t/h to ~18 t/h altogether.

Comparing the heat load of the steam on the discharge side (~12 MW) with the nominal overall electrical power demand for both compressor units (~2.25 MW), a COP of ~5.3 is seen. Summarized, the nominal key figures for the two installed steam compressors are:

- 6-cylinder steam compressor + 3-cylinder steam compressor (each for double stage steam compression)
- Inlet steam: 5.0 bar(a) (saturated; ~152 °C)

- Outlet steam: 19.5 bar(a), (superheated with ~240 °C; sat. temp. ~211 °C)
- Steam flow rate (suction side): 11 t/h + 5.5 t/h
- Steam flow rate (discharge side): 12 t/h + 6 t/h
- El. power demand: 1.5 MW + 0.75 MW
- Heat load steam (discharge side)*: ~8 MW + 4.0 MW

*condensing heat + heat from condensate subcooling down to 105 °C.

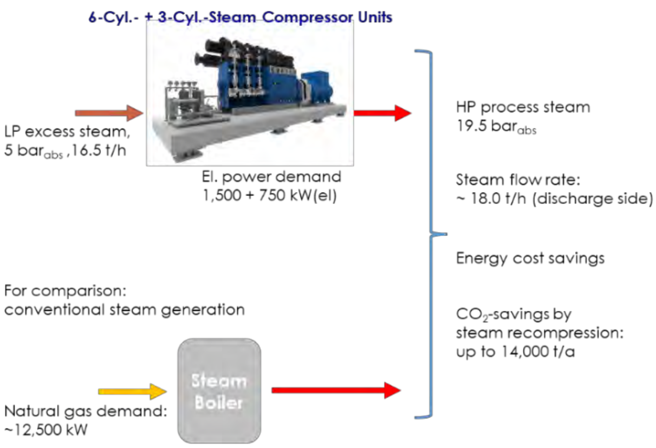

Figure 2: Steam parameters of steam compressor installation at chemical plant, United Kingdom.

Operating experiences

The installation of the new production line in the chemical plant took longer than originally planned. Therefore, the final commissioning of the steam compressors did not take place until summer 2021. During commissioning it was shown that the steam compressors have a better delivery rate than expected. They reach their nominal flow rates even at < 900 RPM (instead of 1,000 RPM full speed). Also their specific electrical power consumption is about 10 % lower compared to the nominal figures as described above, so in practice the resulting COP of the compressor units is even better (with COP_{real} > 5.8).

By recycling the 5.0 bar(a) excess steam via a steam compressor to 19.5 bar(a) process steam, compared to a conventional 19.5 bar(a) steam production with natural gas fired boiler, CO_2-savings of around 14,000 t/year are resulting. This is based on assumption with 7,500 full load operating hours, and CO_2-emissions of the UK electricity mix (year 2016) of ~0.281 kg/kWh.

FACTS ABOUT THE CASE

Installation year: 2018
Operating hours: n/a
Working fluid used: R-718 (water)
Compressor technology: Piston
System manufacturer: Spilling Technologies GmbH
Performance in design point:

- **Heat source:** 5.0 bar(a) steam with 152 °C
- **Heat sink:** 19.5 bar(a) steam, 240 °C (superheated), sat. temperature~ 211 °C
- **Heat supply capacity:** 12 MW
- **$COP_{Heating}$:** 5.3. This is based on condensing heat and heat from condensate subcooling to 105 °C in ratio to the compression power. The figure belongs to the contractual guaranteed max. electrical power demand of the compressor units, in practice it is even better with COP_{real} > 5.8. The electrical power demand and the heat load of the steam were validated by the customer during handover procedure.

Investment cost: 2,200,000 € without cost for integration.
Savings: unknown
Estimated annual CO_2 savings: 14,000 t/year

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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.

Steam compressor for steam recycling at pulp drying with pressurized superheated steam dryer (PSSD)

Figure 1: Steam compressors during installation at paper mill, Sweden.

Summary of demonstration case

At a paper mill in Sweden, about 200 km west of Stockholm, pulp is dried with a pressurized superheated steam dryer (PSSD). The internal steam cycle of this dryer is superheated by a heat exchanger heated with 16 bar(a) steam. From the PSSD, exhaust steam from the dried pulp is evaporating with a pressure of ~ 3.5 bara. This exhaust steam, contaminated with particles, is used as heat source to produce clean steam in a so called "Reboiler", leaving it with ~ 3.2 bara. The 3.2 bara clean steam is now compressed to 16 bara again by two Spilling steam compressors (each with 6 cylinders, double stage), to supply the heat source for the dryer (see figure 2). Overall, the dryer/ steam compressor combination is a self-suppling system, no additional steam from an external source is required. The only heat source input into the drying process is the electrical power demand to drive the two compressors.

The two 6-cylinder-steam compressors each consist of four low-pressure (LP) cylinders, compressing the incoming steam in a first stage from 3.2 bar(a) to ~8 bar(a), and two high-pressure (HP) cylinders, compressing in a second stage from ~8 to 16 bar(a). The compressors are equipped with condensate injection equipment for steam cooling at each stage. By this, while steam compression, the quantity of steam is increasing by ~ 10 % between suction side and discharge side.

For the paper mill, from an economical point of view, it was essential to install an energy efficient pulp drying system. The described solution with PSSD dryer and steam compressor for steam recycling (with a COP of ~4.2) is ideal for the mill. Not only is it very energy efficient, the electricity is also comparably cheap and fossil free, since they are using large-scale hydropower.

The nominal key figures for the two installed Spilling steam compressors are:

- Inlet steam: 3.2 bar(a) (saturated; ~ 135 °C)
- Outlet steam: 16 bar(a), (superheated with ~240 °C; sat. temp. ~201 °C)
- Steam flow rate (suction side): 2 x 8 t/h
- El. power demand: 2 x 1,325 kW
- Heat load steam (discharge side): ~2 x 5,600 kW*
- COP: >4.2

*condensing heat + heat from condensate subcooling down to 105 °C.

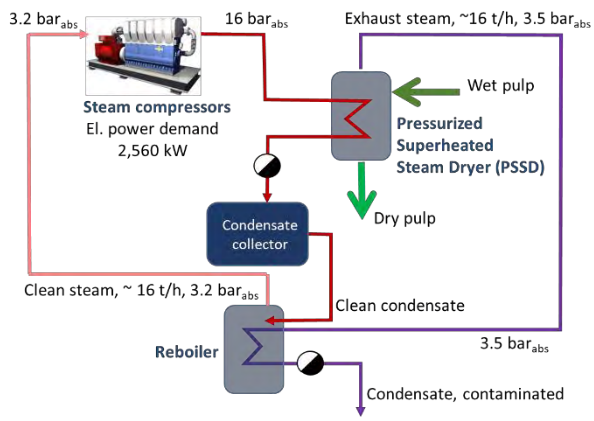

Figure 2: Steam compressor for steam recycling at pulp drying with PSSD dryer.

Operating experiences

In practice, the steam compressors have a better delivery rate than expected. They reach their nominal flow rates even at <900 RPM (instead of 1,000 RPM full speed). Also their specific electrical power consumption is about 10 % lower compared to the nominal figures as described above, so in practice the resulting COP of the compressor units is even better (with COP_{real} > 4.7).

By recycling the steam evaporated from the PSSD dryer, compared to a conventional steam production with natural gas fired boiler, and considering the real el. power demand/COP_{real}, CO_2-savings of around 14,000 t/year are resulting. This is based on 6,000 full load operating hours, and CO_2-emissions of Swedish electricity mix: ~0.013 kg/kWh

Special learnings

By optimizations at the PSSD dryer and temporary operation of the system with lower discharge pressures (down to ~13 bar(a) instead of ~16 bar(a)), the electrical power demand of the steam compressors is again lower than at nominal pressure parameters, and thus the COP/energy savings are even higher than described above.

FACTS ABOUT THE CASE

Installation year: 2016
Operating hours: Over 7,500 hours/a
Working fluid used: R-718 (water)
Compressor technology: Piston
System manufacturer: Spilling Technologies GmbH
Performance in design point:

- **Heat source:** 3.2 bar(a) steam with 133 °C
- **Heat sink:** 16 bar(a) steam, 240 °C (superheated), sat. temperature~ 201 °C
- **Heat supply capacity:** 11.2 MW
- **$COP_{Heating}$:** 4.2. This is based on condensing heat and heat from condensate subcooling to 105 °C in ratio to the compression power. The figure belongs to the contractual guaranteed max. electrical power demand of the compressor units, in practice it is even better with COP_{real} > 4.7. The electrical power demand and the heat load of the steam were validated by the customer during handover procedure.

Investment cost: 2,500,000 € without cost for integration.
Savings: unknown
Estimated annual CO_2 savings: 14,000 t/year

Contact information

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DryFiciency - Industrial heat pump for a climate-neutral European industry

Figure 1: *DryFiciency Heat Pump at Wienerberger brick production facility in Uttendorf, Austria*

Summary of demonstration case

In the H2020 project DryFiciency, high temperature heat pumps were developed and demonstrated to supply process heat with up to 160°C for industrial drying processes to increase energy efficiency and to lower CO_2 emissions. Wienerberger AG, the largest brick producer in the world, operates around 200 brick dryers. The DryFiciency heat pump was integrated in the brick production process in Uttendorf, Austria, supplying heat for the drying process. A thermally driven heat pump uses hot air from the kiln and moist exhaust air from the dryer to supply hot water at 90°C for the dryers. The DryFiciency heat pump uses the hot water from the thermal heat pump as the heat source and provides hot air at up to 160°C for the last zone of the dryer, where higher temperatures are needed.

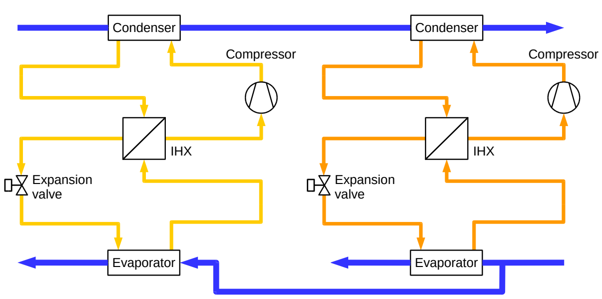

Figure 2: Layout of the DryFiciency heat pump

Johannes Rath, CTO at Wienerberger Building Solutions: "Sustainability has always been at the core of the Wienerberger world. As part of the DryFiciency research project, together with AIT, we were able to set another milestone in the direction of decarbonisation of the brick industry and create a prime example of how innovations from research can be brought to market quickly"

It is a closed loop vapor compression heat pump, the development and demonstration work included:

- **The use of the synthetic low GWP refrigerant R-1336mzz(Z) by Chemours**
- **8 piston compressors designed for high temperature applications by Viking Heat Engines**
- **Fine-tuned, synthetic lubricant working stable with the refrigerant by Fuchs Schmierstoffe**

- **Refrigerant cycle designed as twin cycle for efficient operation over a wide range of operation conditions**

Operating experiences

The DryFiciency heat pump was operated for more than 4000 h covering a large range of operation conditions (heat supply temperatures from 104°C – 160°C, design point at 120°C). Compared to a natural gas burner providing the same amount of process heat, the DryFiciency heat pump reduces end energy consumption by 2200 MWh/a, primary energy consumption by 1900 MWh/a, CO_2 emission by 590 t/a, resulting in 60500 €/a of energy cost savings. The increase in drying air temperature in the last zone of the dryer has beneficial effects on brick drying time and quality.

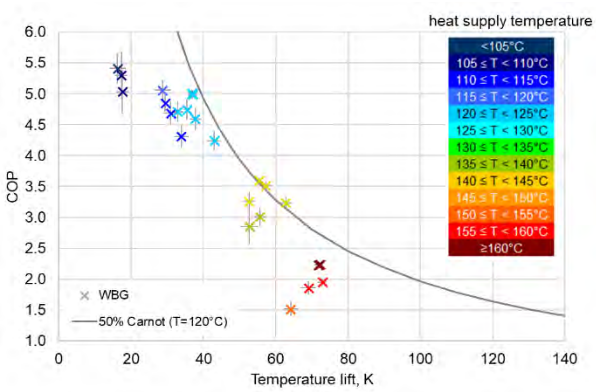

Figure 3: Measured COP of the DryFiciency heat pump at Wienerberger

Special learnings

Challenges encountered during the development of the high temperature heat pumps included material compatibility (lubricant, refrigerant, sealing materials), mechanical design (vibrations), integration infrastructure (e.g. pressure maintenance, flow measurement) and in the process control (e.g. start up procedure, data transfer, measurement devices).

DryFiciency demonstrated the successful component development for high temperature applications such as compressors, lubricant and refrigerant as well as the successful operation of the closed loop heat pumps in industrial environment.

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

FACTS ABOUT THE CASE

Installation year: 2019
Operating hours: over 4,000 hours
Working fluid used: HFO-1336mzz(Z)
Compressor technology: piston compressors
System manufacturer: built by AMT Kältetechnik based on the design by AIT
Performance in design point:

- **Heat source: 88°C → 84°C, water**
- **Heat sink: 96°C → 121°C, water**
- **Heat supply capacity: 296 kW**
- **$COP_{Heating}$: 5.0**

Performance at 160°C heat supply temperature:

- **Heat source: 91°C → 88°C, water**
- **Heat sink: 131°C → 160°C, water**
- **Heat supply capacity: 190 kW**
- **$COP_{Heating}$: 2.2**

Investment cost: -
Savings: 60,500 €/a at 120°C
Estimated annual CO_2 savings: 590 t/a at 120°C
Link to webpage or report: