13th IEA Heat Pump Conference
April 26-29, 2021 Jeju, Korea

High temperature heat pumps for drying – first results of operation in industrial environment

Veronika Wilk[a*], Franz Helminger[a], Michael Lauermann[a], Andreas Sporr[a], Bernd Windholz[a]

[a]AIT Austrian Institute of Technology GmbH, Giefinggasse 2, 1210 Vienna, Austria

Abstract

Heat pumps make an important contribution to increasing the efficiency of industrial processes and avoiding CO_2 emissions and therefore are considered as an important element for industrial heat supply by valorizing waste heat. Heat utilisation temperatures above 120°C will significantly expand the field of application for heat pumps in industry. This article presents the first results of operation of the H2020 project DryFiciency. Closed loop high temperature heat pumps with a heating capacity of 400 kW and heat supply temperatures up to 160°C are being developed, built and operated. The heat pumps are integrated in industrial drying processes recovering waste heat available on site. In this article, a first assessment of the operation of the heat pump for brick drying at Wienerberger AG in Uttendorf (Austria) is presented.

Keywords: High temperature heat pumps; industrial application; drying; HFO refrigerant; demonstation

1. Introduction

Decarbonization of industrial production is a key element to achieve the climate goals of the European Union. This requires drastic reduction of energy consumption and CO_2 emissions, as well as the transition to renewable energy supply. Increasing energy efficiency of industrial processes will contribute significantly to achieve these goals, however, new processes are also needed, such as electrification to replace fossil energy supply. Industrial heat pumps enable both, efficiency increase and electrification and will therefore play a major role in the future energy system.

Although heat pumps are an established technology for domestic heating and hot water preparation, integration of heat pumps into industrial processes is still in an early diffusion phase. Currently, there is no statistical data available on how many heat pumps are already applied in industry. In the framework of the collaborative IEA HPT Annex 48 project, more than 300 application examples for industrial heat pumps were collected from 7 countries. [1] These heat pumps are applied in many different industrial sectors. For example, in Austria a large number of examples is reported for the food industry, utilities and metal processing industry. The heat supply temperatures of the heat pumps in the examples are in the range of 45-95 °C, which corresponds to the products available on the market. Heat pumps supplying that temperature range have been available on the market for many years. [2]

In the last years, new developments have raised the heat supply temperature to more than 100 °C. With heat pumps that deliver high temperature heat up to 160 °C, a larger range of applications in industry can be covered. However, there are some barriers that still slow down the diffusion of heat pumps in industry despite the great application potential. Arpagaus [3] summarized the findings of several studies on market barriers for industrial heat pumps: There are important economic barriers, such as stringent expectations of short payback periods

* Corresponding author. Tel.: +43 664 6207794; fax: +43 50550-6679.
E-mail address: veronika.wilk@ait.ac.at

by industry and competing heating technologies based on fossil fuels at low energy prices. But there are also barriers related to knowledge and trust in a new technology: low level of awareness of the technical possibilities due to further development, lack of knowledge about the integration into industrial processes and lack of pilot and demonstration systems. [3]

Industrial demonstration projects are an important step to address the knowledge-related barriers. Within DryFiciency, an H2020 project, heat pumps for drying processes are developed, constructed and operated in a real industrial environment. Drying processes are among the most energy intense processes; they are wide spread in industry and mostly fired with fossil fuels. The heat pumps are used to recover waste heat that is available at the industrial sites and upgrade it to process heat for drying at temperatures up to 160 °C. In the project, different types of heat pumps are developed: heat pumps for air drying processes based on a closed loop vapor compression system and heat pumps for steam drying based on an open loop mechanical vapor recompression system. The heat pumps for air drying are demonstrated in a starch drying process of Agrana Stärke GmbH, an Austrian company specialized in processing and refining of agricultural raw materials such as corn, wheat and potatoes; and in a brick dryer of Wienerberger AG, the world's largest brick producer. The open loop heat pump for steam drying is demonstrated in a batch dryer for sludge of Scanship Holding AS in Drammen/Norway. First, the industrial drying processes were analyzed in detail, then, the heat pumps and their system integration were designed. A special focus was placed on the selection of materials and compounds to ensure stability and reliability at the demanding conditions of the high temperature applications. The heat pumps were constructed and integrated at the industrial sites. Commissioning of the heat pumps started in November 2019. In this work, a first assessment of the operation of one of the DryFiciency heat pumps are presented: the closed loop heat pump for brick drying at Wienerberger.

2. Brick drying process with heat pump

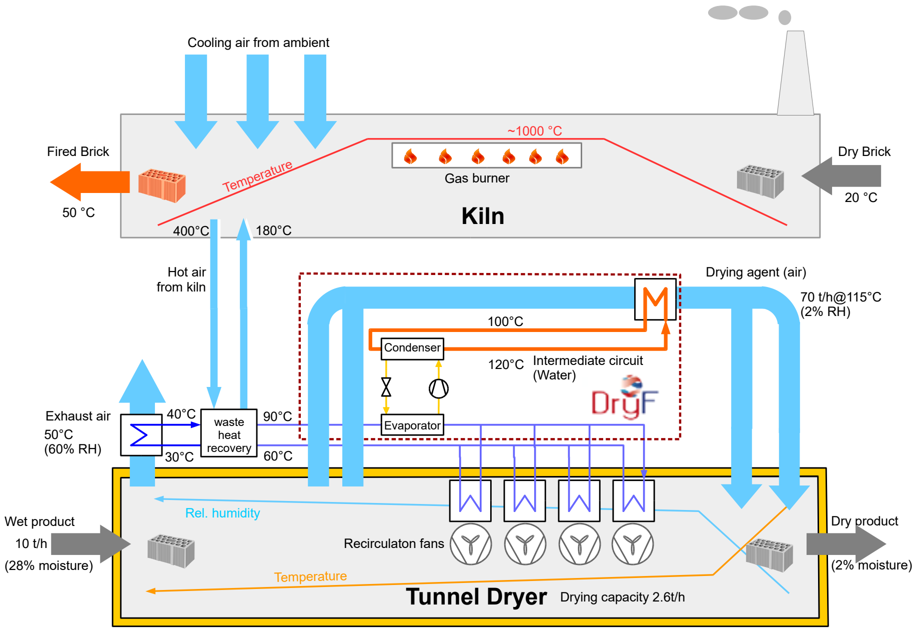

Fig. 1. Illustration of brick drying process at Wienerberger with the DryFiciency heat pump, the indicated temperatures values of the intermediate circuit and the drying agent show the design operating point for the DryFiciency heat pump, the thin red line in the kiln indicates the temperature profile in the kiln, the thin blue and orange lines the temperature and moisture profile in the tunnel dryer.

Wienerberger operates approx. 200 brick dryers in its manufacturing units worldwide. The DryFiciency heat pump was integrated at the production site in Uttendorf in Austria.

In general, the production of bricks and other clay products can be divided into several steps: preparation of the raw materials, shaping of the bricks, drying and firing. The drying process prepares the bricks for firing by extracting moisture from the soft shaped bricks. The shaped bricks (so-called "green" bricks) with a moisture content of around 28 % are dried to a moisture content of 2 % required at the entrance of the kiln. Drying is the most energy intensive step in the brick production process.

The dryer, the kiln and the heat pump are illustrated in Fig. 1. It is a continuous drying process in a tunnel dryer using air as drying agent flowing counter-currently to the bricks. Drying air is heated by internal heat exchanger surfaces in the tunnel, which are supplied with water with 90 °C by a heat recovery cycle. The heat pump also uses the heat recovery cycle as the heat source. The evaporator of the heat pump is installed before the heat exchangers. The heat pump provides hot air via an intermediate circuit, heat supply temperatures up to 160 °C can be reached there. The hot air is fed into the outlet zone of the tunnel dryer, where the highest temperatures are required. The heat pump acts as a booster for the heat recovery cycle. It replaces a natural gas burner, that was used for that purpose.

2.1. Heat pump and integration infrastructure

The heat pump is designed as a closed loop compression heat pump with a heating capacity of up to 400 kW. R-1336-mzz(Z) by Chemours is used as refrigerant, it is based on HFO (hydrofluoro-olefins). The refrigerant has been already successfully tested at AIT in a lab-scale heat pump prototype for high temperature applications up to 160 °C. [4]. It has a low GWP value of 2 (global warming potential) and is non-flammable, non-toxic and not subject to the F-gas regulation.

The piston compressors integrated in the demonstrator were developed and supplied by Viking Heat Engines AS. The compressor design is based on an ORC (Organic Rankine Cycle) expander used for heat recovery applications with an overall design temperature of 215 °C. The expander has already been extensively tested at high temperatures and achieves high efficiencies. The compressor designed is 90 % the same as the ORC expander and built on the same piston bottom-end, only the cylinder head is different. Over the past five years the piston expander has undergone a comprehensive development program to achieve a long service life and high durability at very high temperatures. Today, this piston machine technology is equally capable of operating in organic Rankine cycles (ORC) as well as vapor compression heat pump systems. The compressor is designed for use with R-1336-mzz(Z). A single piston compressor has a swept volume of 55 m^3/h at 1800 rpm. A total of eight compressors arranged in two modules of four are used. Fuchs Schmierstoffe GmbH has developed a suitable lubricant for the compressors, which fulfils all necessary requirements regarding lubrication, viscosity, and thermal and chemical stability together with the refrigerant.

The heat pump is designed as a twin cycle system consisting of two refrigerant cycles (see also Fig. 5). The condensers of the two cycles are connected in series. Thus, the temperature lift from the heat source to the heat sink is reduced to a certain extend for one of the two cycles and about one half of the heating capacity is provided at a higher COP (coefficient of performance). In each refrigerant cycle there is one compressor module with four compressors. Due to the thermodynamic properties of the refrigerant, an internal suction gas heat exchanger is used to ensure dry compression.

The heat pump is placed in a container with approximately 8 m in length and 3 m in height and width. It is equipped with eight doors to enable easy access and if necessary, replacement of components of the heat pump. It contains all piping and other connections that are needed to connect the heat pump with the integration infrastructure at the brick dryer. Fig. 2 and Fig. 3 show the heat pump container from the outside and with open doors. The heat pump itself consists of hundreds of single parts of the following main component categories:

- Components for the refrigerant cycles such as piston compressors, condensers, evaporators, etc.
- Components for water distribution for the heat source and heat sink including control and safety valves, metal bellows compensator, etc.
- Housing including refrigeration machinery room equipment like ventilation, leakage detection system and warning devices
- Control system including cabinet, programmable controller, frequency converters, electrical fuses, control transformer, visualization, data logging and data transfer equipment to allow profound monitoring activities
- Measurement devices

Fig. 2: Heat Pump Container (outside)

Fig. 3: Heat Pump Container (inside, before insulation)

As illustrated in Fig. 1, the heat pump is integrated into the drying process by an intermediate water circuit. The water circuit allows testing a wide range of heat supply temperatures from 110 – 160 °C. In the intermediate circuit, a pressure holding device including a circulation pump and a water-to-air heat exchanger (air register) are installed.

2.2. Measurement equipment

Monitoring, data logging and data transfer are separated into two parts, one with the existing process control system of Wienerberger, where also the integration infrastructure (intermediate water circuit, air register and heat source) belongs to, and the other one of the DryFiciency heat pump. Both process control systems have their own measurement points and separate data transfer to AIT.

The heat pump is equipped with numerous sensors for data monitoring. Temperature sensors are integrated at all important parts of the refrigerant cycles, for example at the condensers, the internal heat exchanger, the expansion valve, the evaporators and the compressors. Pressure sensors are located among others before and after the compressors, at the inlet of the condensers and before the expansion valves. Electricity consumption of the motors is measured in terms of power, energy, voltage, current and power factor. In addition, heat meters to monitor the heat source and the heat sink are integrated.

Numerous parameters of the drying process from the existing process control system are used to determine the impact of the heat pump on the brick production process. The following parameters from the tunnel dryer are used: Volume flow of drying air into the dryer, inlet and outlet conditions of the air in the dryer, inlet and outlet temperature and mass flow of hot water used in the heat exchanger to heat the tunnel dryer, mass flow of wet bricks, mass reduction of bricks from inlet to outlet of the dryer.

3. Results

During commissioning, a trial operation of the heat pump system is carried out to provide proof of operational safety and functional capability. Also, the quality of the heat pump system is assessed based on fundamental functional tests according to predefined operating conditions to test the control algorithms, compressor lubrication, oil separation, operating temperatures of the compressors the suction gas super heating and part load conditions. The successful completion of the trial operation is the end of the commissioning and an important prerequisite for the subsequent long-term monitoring. Four different operation conditions are described in more detail that are characterized by different heat supply temperatures: 120, 140, 150 and 160 °C (Table 1).

Table 1: Operation points during trial operation

Operation point	Heat sink inlet temp., °C	Heat sink outlet temp., °C
1	95	120
2	110	140
3	120	150
4	130	160

Fig. 4 illustrates the heat source and heat sink inlet and outlet temperatures for the four operation points. The yellow area indicates the preparation phase, the green area stationary operation. For OP1, 2 and 3, stationary operation lasted more than three hours and did not show any fluctuations in the heat source and heat sink. For OP4, operation was shorter and lasted about one hour. The heat source inlet temperature was 88 °C for all operation points. The complete heat source mass flow was used for the heat pump without flow regulation, as a result, the heat source was cooled by 3 – 6 K.

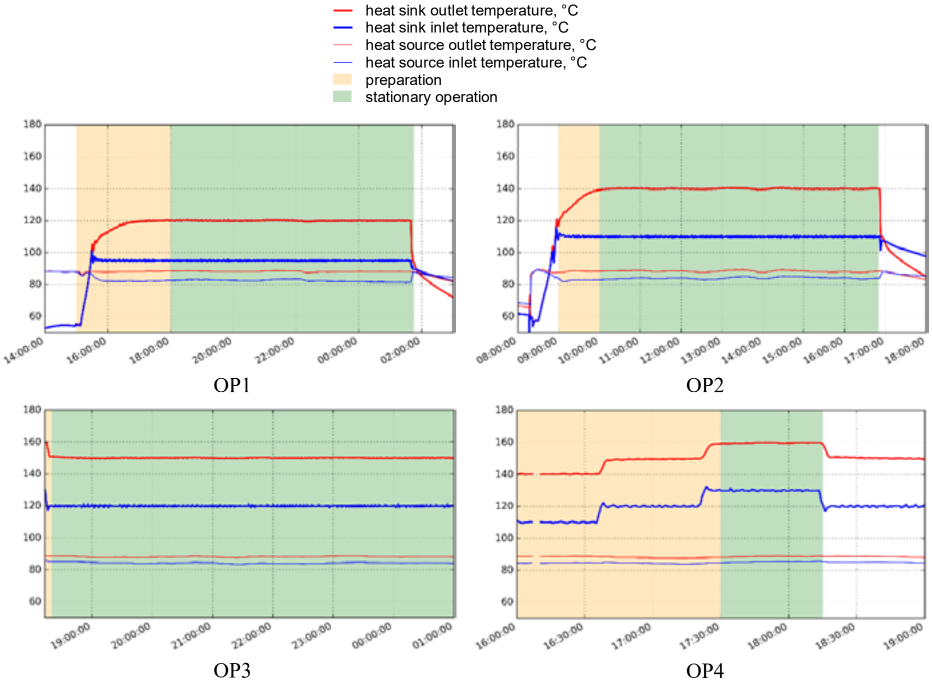

Fig. 4: Time series diagrams for four different operation points (120, 140, 150 and 160 °C)

As previously mentioned, the DryFiciency heat pump is designed as a twin cycle system consisting of two refrigerant cycles. The layout is shown in Fig. 5. The condensers of the two cycles are connected in series, therefore the condensation temperature of cycle 1 (yellow) is lower than the condensation temperature of cycle 2 (orange). The evaporators can be either operated in series or parallel. For the trial operation, they were operated in parallel. Fig. 6 shows the log(p)-h diagram for both cycles for OP1 (120 °C). The section 1-2 takes place in the compressor, 2-3 in the condenser, 3-4 in the sub-cooler, 4-5 at the hot side of the internal heat exchanger (IHX), 5-6 in the expansion valve, 6-7 in the evaporator and 7-1at the cold side of the internal heat exchanger. Due to the sub-cooler, more heat can be supplied to the industrial process. The sub-cooler is integrated between the condenser and the internal heat exchanger (not illustrated in Fig. 5). In cycle 2, more heat is provided in the sub-cooler than in cycle 1. For both cycles, the evaporation temperature amounted to 78 °C. As indicated by point 7, the refrigerant leaves the evaporator with super heat. The internal heat exchanger increases the efficiency by transferring heat from the high pressure side to the low pressure side of the heat pump. Point 1 and 2 indicate the satisfying function of the super heat control to ensure dry compression. The difference in condensation temperature between cycle 1 and cycle 2 was 10 K.

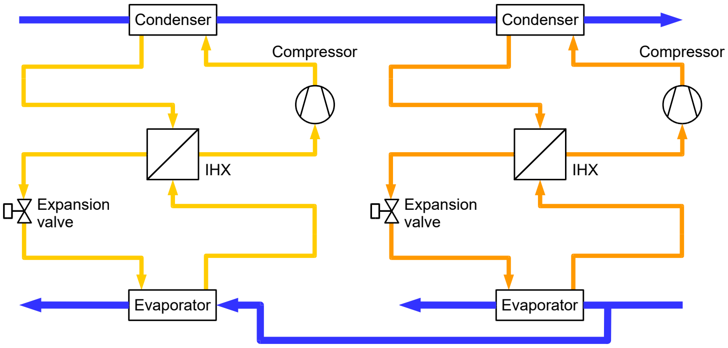

Fig. 5: Layout of the DryFiciency heat pump (yellow = cycle 1, orange = cycle 2)

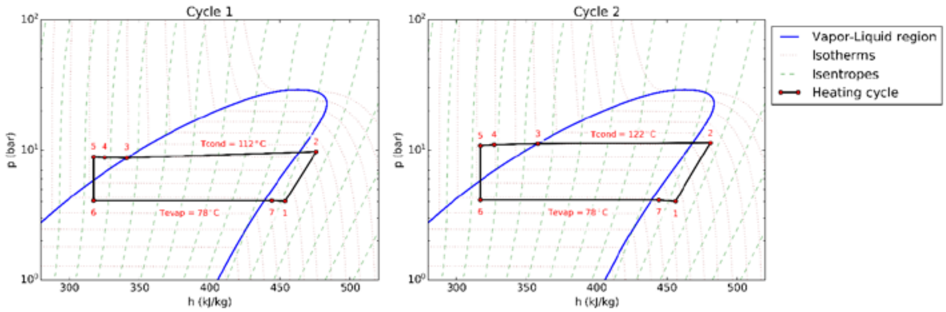

Fig. 6: Log(p)-h diagram for cycle 1 and 2 of the heat pump, OP1 (120 °C)

OP2, OP3 and OP4 show similar behavior as illustrated in Fig. 7, Fig. 9 and Fig. 10. With increasing temperature lift, more compressor work is needed to achieve higher discharge pressures. At a heat supply temperature of 160 °C, condensation takes place at the upper end of the vapor dome close to the critical point. With increase in supply temperature, the beneficial effect of the internal heat exchanger becomes more apparent. More superheat is needed at higher temperatures because of the shape of the vapor dome of R-1336mzz(Z).

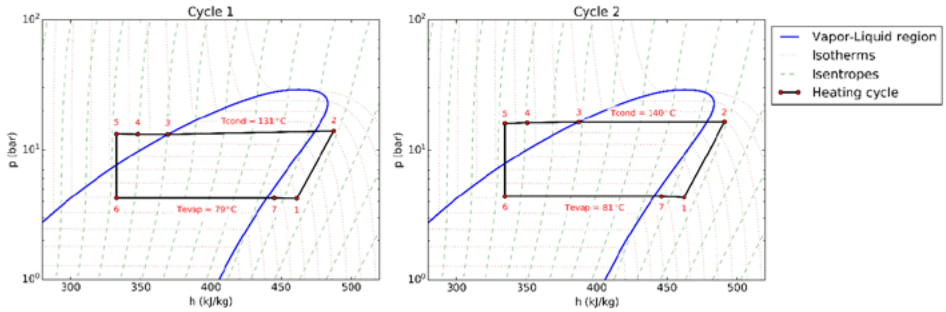

Fig. 7: Log(p)-h diagram for cycle 1 and 2 of the heat pump, OP2 (140 °C)

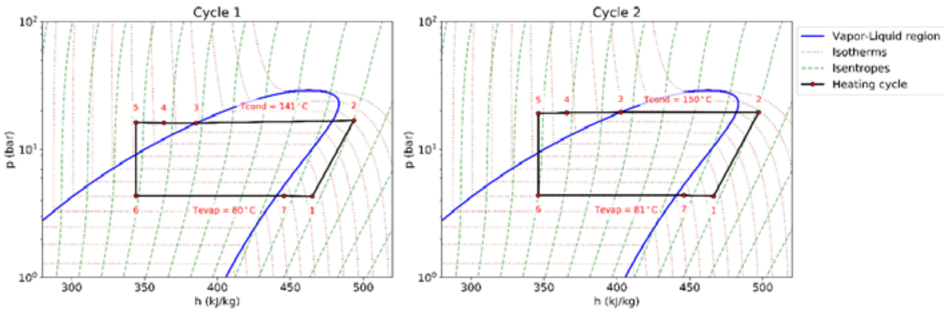

Fig. 8: Log(p)-h diagram for cycle 1 and 2 of the heat pump, OP3 (150 °C)

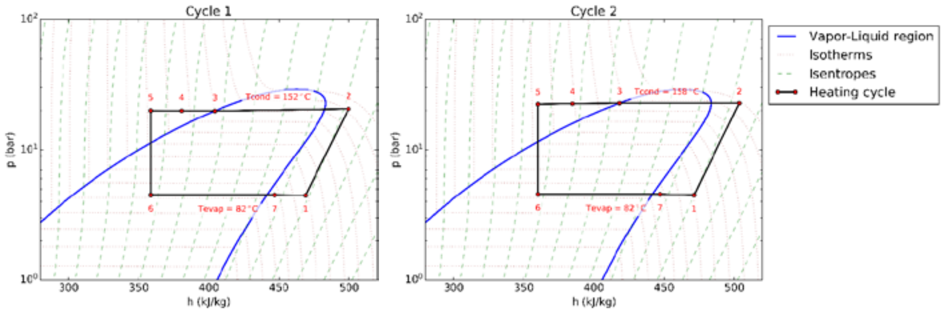

Fig. 9: Log(p)-h diagram for cycle 1 and 2 of the heat pump, OP3 (160 °C)

In Table 2, energy flows, mass flows and temperatures are compiled for the trial operation. The compressors were operated at 1500 rpm. Q_{heat} is the sum of the heat transferred to the industrial process in the condenser and in the sub-cooler, ranging from 200 – 300 kW for the trial operation. Q_{cool} is the heat extracted from the heat source in the evaporator, ranging from 150 – 240 kW. For OP1, the COP is the highest due to the smallest temperature lift of 40 K. It amounted to 4.65. At OP4 (heat sink outlet temperature of 160°C), the COP was 2.66.

In Fig. 9, the DryFiciency heat pump is compared with various other industrial high temperature heat pumps that were compiled by Arpagaus [3]. Data comprises heat pumps by different manufacturers, such as Kobelco, Viking Heat Engines, Ochsner, Friotherm, Combitherm, GEA, Star Refrigeration, etc. All these heat pumps have heat supply temperatures exceeding 90 °C covering the whole range of heating capacities from 30 kW to more than 10 MW. The lines in Fig. 10 indicate the COP of a heat pump with heat supply temperatures of 120 °C and 160 °C that reaches 50 % of the COP of the ideal Carnot process (Second law efficiency). The COP of the DryFiciency heat pump is in good agreement with efficiency data from the other industrial heat pumps and ranges among the higher values that were reported. The second law efficiency of the DryFiciency heat pump is in the range of 50 %. The comparison shows that the trial operation of the DryFiciency heat pump was highly satisfactory.

Table 2: Operation points during trial operation

OP	Qheat, kW	Qcool, kW	Pel, kW	COP	Vsink, m³/h	Vsource, m³/h	Tsink_in, °C	Tsink_out, °C	Tsource_in, °C	dTsource, K
1	281.7	239.0	60.6	4.65	9.9	33.3	95.8	120.9	88.3	6.5
2	254.0	208.5	68.5	3.71	7.5	45.5	110.7	140.9	88.4	4.2
3	221.2	174.3	69.6	3.18	6.5	37.6	120.7	150.9	88.4	4.3
4	195.9	148.4	73.8	2.66	5.9	42.3	130.7	160.7	88.6	3.3

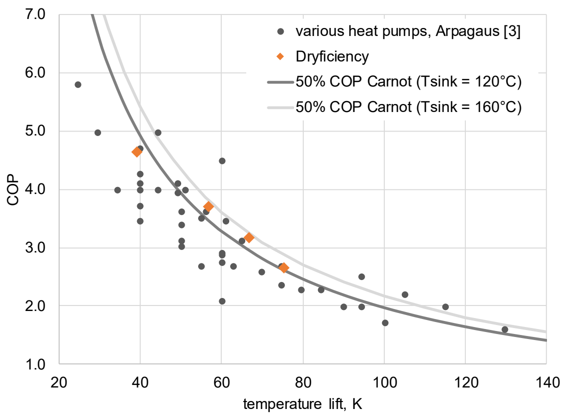

Fig. 10: Comparison of the COP of the DryFiciency heat pump and other industrial heat pumps, based on data from Arpagaus [3]

4. Conclusion

In this article, a first assessment of the operation of the DryFiciency heat pump for brick drying at Wienerberger AG in Uttendorf (Austria) is presented. It was commissioned in November 2019 recovering waste heat at around 90 °C and providing hot air for the brick dryer. It is the first demonstration of a high temperature heat pump in real industrial environment providing up to 160 °C. During trial operation, the basic functionality of the heat pump was assessed. Four different operation points with varying heat supply temperatures were analyzed in more detail. Trial operation proved that the heat pump is working in stationary conditions without any fluctuations of the heat source or heat sink covering the whole range of 120 – 160 °C. Due to the twin cycle layout of the refrigerant cycle, the condensers are arranged in series with a temperature difference of 10 K in condensing temperature. Suction gas and discharge gas super heat are important to ensure dry compression because of the thermodynamic properties of the refrigerant. An internal heat exchanger provides the super heat and increases the efficiency of the refrigerant cycle. A comparison of the COP of the DryFiciency heat pump and various other industrial high temperature heat pumps confirms that the DryFiciency heat pump is among the most efficient devices. The results of the trial operation prove that brick drying is more efficient when using a high temperature heat pump, because it decreases energy consumption and provides a higher drying air temperature in the final drying zone in the brick dryer. Future work focuses on long term stability of the heat pump and its components such as refrigerant, lubricant and compressors.

5. Acknowledgement

The project has received funding from the European Union’s Horizon 2020 programme for energy efficiency and innovation action under grant agreement No. 723576.

6. References

[1] Jakobs R, Successful Applications of Industrial Heat Pumps, Workshop WS4, 25th IIR International Congress of Refrigeration, Montreal, 2019.
[2] Wilk, V, Fleckl, T, Arnitz, A, Rieberer, R. Industriewärmepumpen in Österreich: Status Quo und Potentiale, 11. Internationale Energiwirtschaftstagung, Vienna, 2019.
[3] Arpagaus C, Bless F, Uhlmann M, Schiffmann J, Bertsch S, High temperature heat pumps: Market overview, state of the art, research status, refrigerants, and application potentials, Energy (152), p.985-1010, 2018.
[4] Helminger F, Kontomaris K, Pfaffl J, Hartl M, Fleckl T, Measured Performance of a High Temperature Heat Pump with HFO-1336mzz-Z as the working fluid, ASHRAE 2016 Annual Conference, St. Louis, Missouri, 2016.