2024 TECHNICAL UPDATE

Program on Technology Innovation: Industrial High-Temperature Heat Pumps

Technology and Market Introduction

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ABSTRACT

Industrial electrification and decarbonization are gaining national interest as U.S. manufacturing companies aim to reduce their emissions and carbon footprint. Industrial heat pumps provide an efficient electrification solution to incumbent natural gas boiler technologies traditionally used in manufacturing processes. This report serves as an introduction to industrial heat pump technology, associated benefits and barriers, and anticipated upcoming development. It also includes several industrial heat pump implementation case studies.

Keywords

Emissions reduction
Industrial decarbonization
Industrial heat pumps
Industrial electrification
Process heating

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1 BACKGROUND

Energy in Industry

U.S. manufacturing accounts for 33% of total United States energy consumption (USDOE, EIA, 2023) and 23% (USEPA, 2023) of the country's carbon emissions. Process heating is the dominant energy usage in manufacturing accounting for 51% [1] of total onsite energy use. Industrial boiler systems, producing both steam and hot water, are currently used to provide required industrial process heating. According to the U.S. Department of Energy, it is estimated that approximately 35% of industrial energy input for process heating is lost as waste heat. This waste heat may take the form of exhaust gases, cooling water, and heat loss from product heating. At scale, this waste heat inventory in the industrial sector in the U.S. is estimated on the order of 1500-3000 trillion BTU/year. Manufacturing companies are under increased global pressure to adapt these fossil-fuel fired industrial boiler systems to electrified solutions that take advantage of existing waste heat resources.

What is an Industrial Heat Pump?

"At their simplest, heat pumps are devices that move heat from low to high temperature, often using a vapor compression system similar to the heat pump space heating systems used in homes and buildings or in refrigerators. However, industrial heat pumps (IHPs) are more complicated, tailored to meet the diverse needs of industrial processes, and they are usually integrated with one or more such processes." [1].   IHPs move heat from a heat source to a heat sink as shown conceptually in Figure 1. Energy input to drive the heat pump can be electricity or heat. IHPs offer an electrified solution to replace (or complement) industrial boiler systems in U.S. industry.

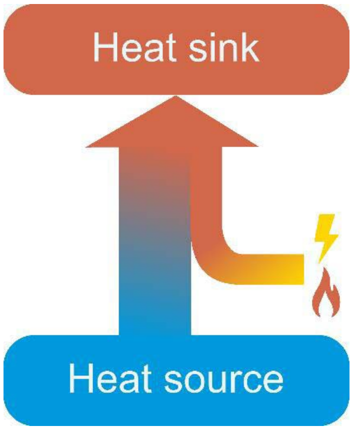

Figure 1. Fundamental Principle of a Heat Pump - Conceptual Diagram (source: IEA Annex 58, 2023)

2 TECHNOLOGY INTRODUCTION

History of Industrial Heat Pumps

While IHP systems have garnered increasing attention in recent years, the concept and underlying technologies of industrial heat pumps aren't particularly novel. In the mid 1980's, EPRI began its work in the IHP space and published several Resource Guide reports, Tech Commentaries and Tech Applications on the topic of industrial heat pumps. This work continued into the 1990's with more specific research documented on specific IHP applications in food processing, chemical production and petroleum refining.

Working Principles of Industrial Heat Pumps

IHP process heating systems use a thermodynamic process similar to refrigeration to transfer heat from the environment, including waste heat streams, to produce hot water and steam. IHP systems can produce hot water and steam for use in various industrial processes. IHP systems are engineered to fit the precise needs of the industrial process they are intended for. Because of their use of the refrigeration cycle, IHPs offer increased efficiency when compared to both incumbent natural gas boilers and alternate industrial electrification technology like electric resistance or electrode boilers. In addition to producing hot water and steam, IHPs can be used to dry industrial products, such as lumber, bricks, grain, fish, and fine chemicals.

Each industrial sector has a different range of heat sink temperature requirements for their various processes. In the U.S., IHPs are generally currently available at a commercial scale with heat sink or output temperatures up to ~80°C. Newer heat pumps are being introduced to produce low pressure steam up to ~120°C. The favored steam producing IHP applications ~80°C include using waste (or source) heat that is available around ~65°C. The top three industries that currently have the greatest potential to use IHPs are Food and Beverage, Chemical Manufacturing and Pulp and Paper due to their favorable temperature requirements. IHPs can be used in a variety of specific processes within these industries including sterilization, air preheating, production of low-pressure steam, hot water production, and more.

Benefits and Barriers of Industrial Heat Pumps

IHPs offer industrial customers several benefits not offered by incumbent natural gas boiler technology. IHPs can provide energy-saving opportunities with the potential to reduce energy used in process heat generation by as much as one-third. In turn, IHP operation may result in lower energy cost. Operating and maintenance costs can be reduced further through economic incentives and development of a skilled workforce. IHPs offer enhanced sustainability when compared to alternative systems given their efficiency and produce no on-site emissions. Additionally, there is no risk of fuel leakage with the use of IHPs. Finally, IHPs offer opportunities for equipment downsizing through use of waste heat recovery and incorporation of dual heating and cooling capabilities.

Despite these benefits, IHP uptake has been minimal in the U.S. and does not come without barriers. There is a high initial investment cost required for implementation of IHPs that varies based on site-specific conditions. However, the potential energy savings and reduced operating costs combined with manufacturer rebates, tax credits, particularly through Section 48C of the Inflation Reduction Act, and local utility promotions may make implementation of IHPs more economically feasible. Another barrier is limited product availability in the U.S., as only a few manufacturers currently supply IHPs. Additionally, there is limited IHP applicability for high temperature processes, though ongoing research and development are focusing on increasing the operational temperature range of IHPs. IHP application is often a custom solution that requires engineered design. Unlike electrification and decarbonization technologies found in the residential and commercial sectors, IHPs are not a drop-in replacement for incumbent natural gas boiler technology. Other barriers include lack of in-house IHP expertise at industrial facilities, lack of designer experience with incorporating IHPs in industrial process design, and energy price vulnerabilities.

Developing and Commercially Available Industrial Heat Pumps

Industrial heat pumps are in a growing industry, and as such manufacturers are actively developing new heat pump models to meet different industrial needs. Figure 2 below illustrates available industrial heat pump capacities and supply temperatures, listed by manufacturers as commercially available (mainly in Europe). This data is from IEA/HPT Annex 58, which regularly collects manufacturer product data for industrial heat pumps.

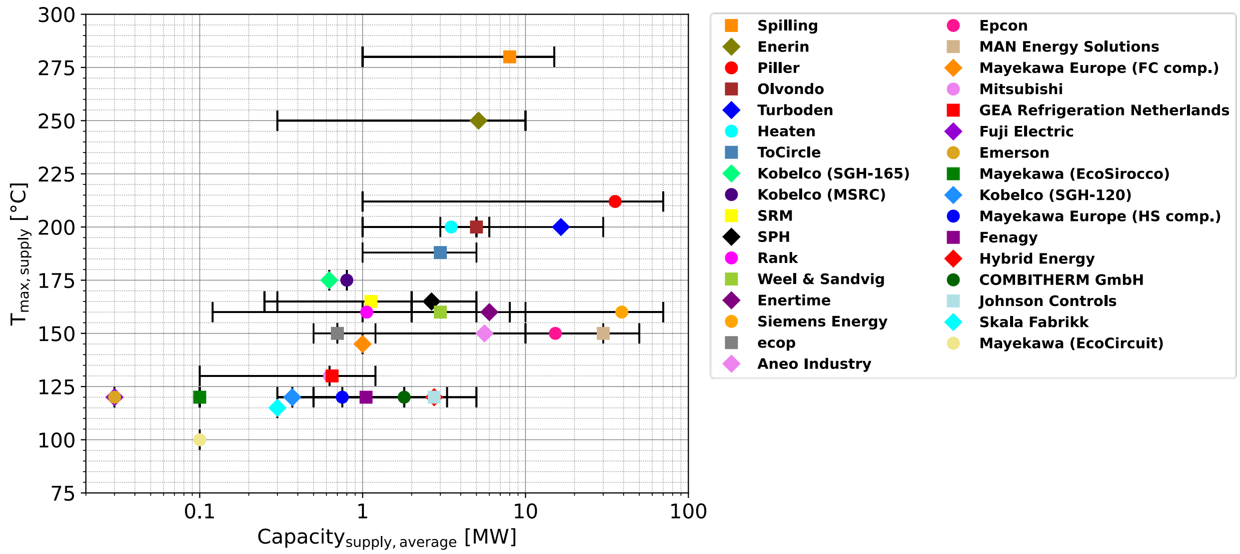

Figure 2. Models of Industrial Heat Pumps Available Commercially. Source: IEA Annex 58 [2]

As illustrated in the figure above, the majority of IHP manufacturers produce products with supply temperatures at or below 200° C. It is also important to note that not all the IHP manufacturers included in the figure above have products available for use in the United States.

3 ANTICIPATED IHP DEVELOPMENT

What's Next?

Industrial heat pump technology is rapidly advancing [4]. As the technology advances and additional domestic case studies for implementation of industrial heat pumps are established, it is anticipated that industrial heat pumps will be more widely used in industry in the U.S. Industrial heat pumps have been implemented in several applications in Europe, Japan, and Australia. There are several case studies of industrial heat pump applications in a variety of facilities including brick manufacturing facilities, transformer manufacturing facilities, and food processing facilities. More information on these case studies is available in Appendix A.

The IHP marketplace in the U.S. includes limited IHP options for supply temperatures above ~80^{o}C. However, there are heat pumps available on the marketplace today that could be implemented in light industrial applications with supply temperatures up to ~80^{o}C. This supply temperature is a good fit in some food and beverage manufacturing, pulp and paper, and industrial chemical processes. EPRI has ongoing project work focused on light-industry applications of industrial heat pumps that is scheduled to be published in 2024, which aims to provide more information on how an industrial heat pump could be applied in specific industrial processes. It is anticipated that as interest and experience with IHPs grow in the U.S., an increased number of global IHP manufacturers will work to provide their products within the U.S. marketplace.

In addition to light-industrial project work, EPRI remains actively engaged in pushing the envelope of industrial heat pump technologies through equipment prototype development and testing. For instance, sponsored by the CEC, EPRI created a prototype IHP that provides low pressure steam with temperatures >120°C [3]. In general, it is anticipated that use of advanced refrigerants will expand IHP output temperatures to up to 150°C.

In addition to the aforementioned projects, EPRI remains engaged as a leader within the IHP realm. EPRI continues to work actively within the industry through engagement with leading R&D organizations and manufacturers in Europe and Japan, engagement in IEA Annex 58, organization of IHP workshop which engaged stakeholders at the Electrification 2024 conference, and ongoing participation and presentations at other IHP focused events.

A KEY CASE STUDIES

Background

The below case studies demonstrate how industrial high temperature heat pumps have been used in light industrial settings. The projects chosen as case studies for this report are intended to help potential light industrial users of high temperature heat pumps understand how heat pumps might fit into their application. All three projects employ mechanical vapor compression (MVC) heat pumps. MVC heat pumps are the most suitable for modular light industrial applications due to their high modularity factor and availability. The case studies examined include a brick factory, an electrical transformer factory, and a food processing application.

Case Study 1: Wienerberger Brick

Wienerberger operates 197 production sites in 29 countries and is the largest brick manufacturer in the world. Its plant in Uttendorf, Austria was fitted with a high temperature heat pump to offset heat normally provided by burning natural gas as part of the Austrian Institute of Technology (AIT) DryFiciency project. The MVC heat pump uses waste heat from the brick kiln and brick dryer exhausts to produce hot air for the brick dryer. The waste heat source is 90°C water that is produced by air-to-water heat exchangers located remotely in the kiln and dryer air exhausts. The heat produced by the heat pump is supplied back to the brick dryer as hot air at 110°C to 160°C. The heat pump was installed in 2019. After more than 4000 hours of operation, energy savings add up to around 80% and have resulted in a reduction in CO_2 emissions of about 80%.

This heat pump was designed by AIT then custom-built by AMT Kältetechnik and uses the refrigerant R-1336mzz(Z). It is fully integrated into a 20-foot shipping container and uses multiple piston compressors built by Viking Heat Engines (now Heaten AS). The compressors are designed to work up to 215°C and are compatible with all 3rd and 4th generation HFC refrigerants. All additional equipment such as piping, electrical, pressure vessels, circulation pumps, and heat exchangers are fitted inside the shipping container with hot air and hot water process connections provided on the outside of the container. It is equipped with multiple doors for easily accessing and maintaining the components.

At the design point of 88°C-84°C heat source and 96°C-121°C heat sink, it provides 296 kW at a COP of 5.0. At the design point of 91°C-88°C heat source and 131°C-160°C heat sink, it provides 190 kW at a COP of 2.2.

Figure 3. Exterior and Interior Views of Heat Pump used at Wienerberger Uttendorf (Schneeberger et. al)

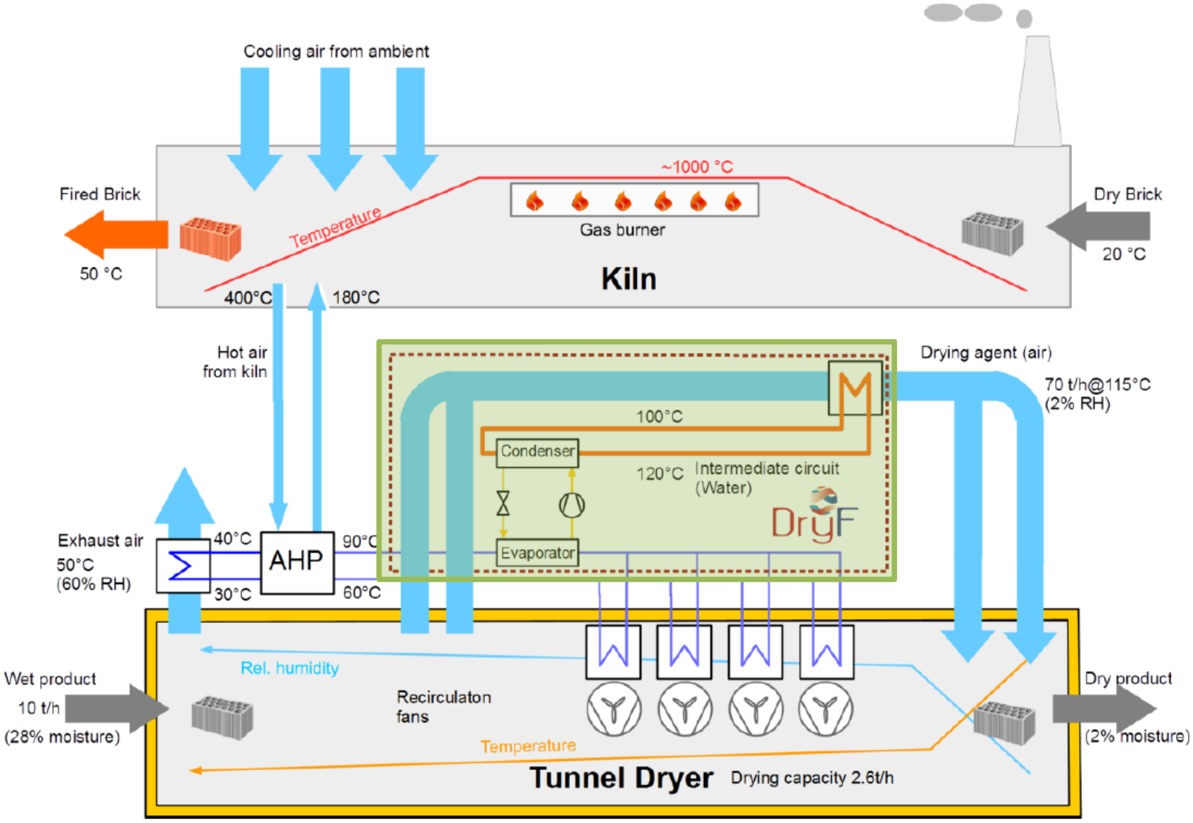

Figure 4. Wienerberger Uttendorf Brick Drying Process with Heat Pump Shown in Green (Schneeberger et. al)

Case Study 2: Takaoka Toko Transformers

Takaoka Toko Co., Ltd. produces electric transformers at its Power Equipment Division Headquarters in Oyama, Japan. During manufacturing, transformers are coated with a special resin that is heated and dried. As part of a Japan Electro Heat Center (JEHC) project, a high temperature MVC heat pump was installed in 2012 in place of a fossil-fuel fired steam boiler normally used for this process. The waste heat source is 55°C water that is produced by air-to-water heat exchangers located in the exhaust of the drying and annealing processes. The heat pump produces 130°C pressurized water that is fed to a water-to-air heat exchanger located at the transformer dryer inlet. This heat exchanger provides 125°C hot air to the dryer. A fossil fuel-fired boiler connected via heat exchanger to the heat pump outlet and available for the backup. Since operation time of both source processes are not the same, a thermal energy storage tank was installed to collect this heat and provide a stable heat source of the heat pump. Energy savings have been around 65% and have resulted in a reduction in CO_2 emissions of about 60%. As a positive side effect of using dry air versus steam, drying time was reduced by 3 days.

The heat pump used for this project is a commercially available (in Japan since 2011) Mitsubishi Heavy Industries Thermal Systems (MHI Thermal Systems) ETW-S high temperature heat pump. It uses a two-stage centrifugal compressor with the refrigerant R-134a and can produce hot water up to 130°C.

At the design point of 55°C-50°C heat source and 70°C-130°C heat sink, it provides 627 kW at a COP of 3.0.

Figure 5. Mitsubishi Heavy Industries Heat Pump used at Takaoka Toko Oyama (Annex 58)

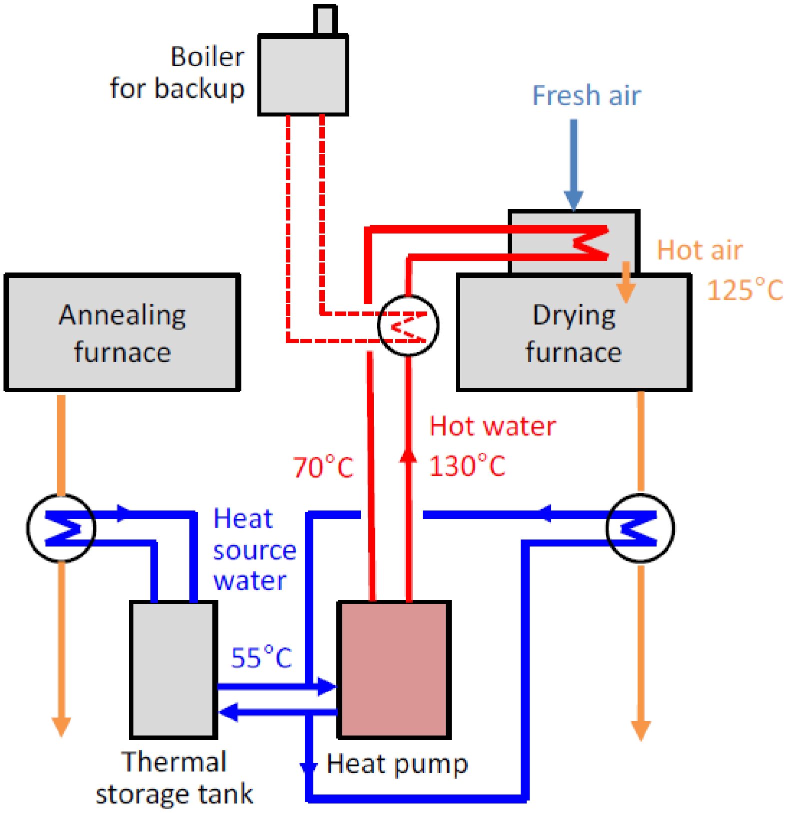

Figure 6. Takaoka Toko Oyama Transformer Heating and Drying Process with Heat Pump Shown in Pink (Annex 58)

Case Study 3: Zennoh Kagoshima Chicken

Zennoh Kagoshima Chicken Foods Corporation processes more than 30,000 chickens per day at its Osumi, Japan factory. One of the processes involved is scalding the chickens to remove their feathers. The feathers of each chicken absorb approximately one liter of water that is ultimately sent to the drain. This process uses a large amount of water heated from room temperature, making the heating load very large. An oil-fired steam boiler was replaced with a high temperature MVC heat pump that uses outdoor air as a source of heat in 2008. The heat pump produces 65°C water overnight that is stored in a 10,000-liter hot water storage tank. Hot water from this tank is fed into a steam boiler that directly heats the scalding tank. Since the boiler feedwater is significantly preheated from well temperature by the heat pump, the boiler requires less oil to operate. Energy savings have been around 88% and have resulted in a reduction in CO_2 emissions of about 65%. As a positive side effect of storing hot water, shift times have been shortened by a half hour. This case study is a good example of how readily available commercial water heating heat pumps can be used in industry.

The heat pump used for this project is a commercially available (in Japan) Mayekawa Commercial Eco-Cute high temperature heat pump. It uses a reciprocating compressor with the refrigerant R-744 (CO_2) and can produce hot water up to 90°C.

With a 20°C air heat source and 20°C-65°C heat sink, it provides 85 kW at a COP of about 3.5.

Figure 7. Mayekawa Eco-Cute Heat Pump and Thermal Storage Tank at Zennoh Kagoshima Oyama (JEHC)

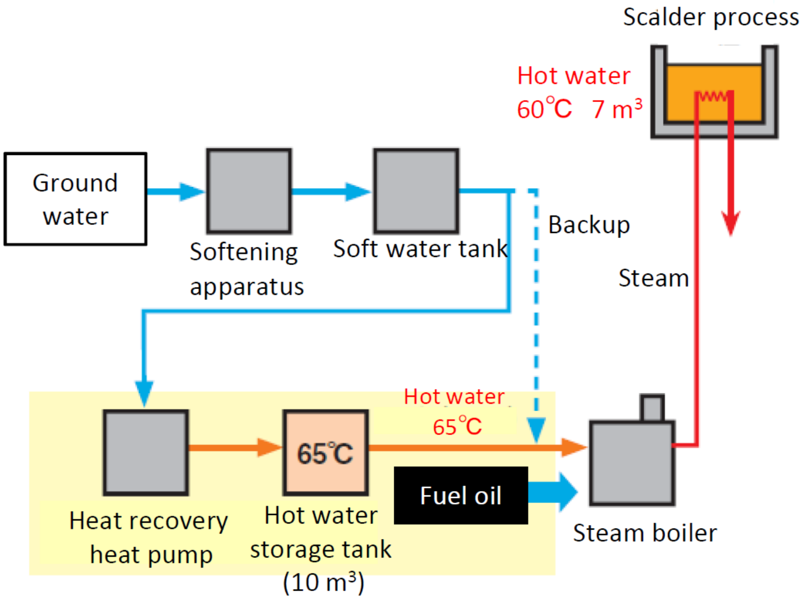

Figure 8. Zennoh Kagoshima Oyama System Diagram (JEHC)

Key Case Study Takeaways

- Thermal storage is important when industrial processes are not synchronous. For source heat storage that is less than 100°C, inexpensive and safe water can serve as a storage medium. For sink heat storage, such as the case with Zennoh Kagoshima, water can also be used as a storage medium. This allows the heat pump to collect energy over a long duration, making the heat pump smaller or serving processes that require more heat per unit of time than the heat pump can produce real-time.
- High temperature heat pumps can be installed in place of or alongside conventional fossil fuel-fired boilers in many applications, making progressive implementation possible.
- High temperature heat pumps can provide lower temperature heat to higher temperature processes, such as feedwater to steam boilers. For processes that do not return boiler condensate, this can save a significant amount of boiler fuel.
- Conventional fossil-fuel fired boilers can be installed as backup heat sources if the heat pump is not trusted by the end-user or if electricity is not available at the time it is needed for the heat pump.

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Case Study Data

The three case studies presented in this paper are derived from the following online resources.

Wienerberger Brick

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Zennoh Kagoshima Chicken

https://www.hptcj.or.jp/Portals/0/english/Learning/Case%20study%E2%91%A2%20Zennoh.pdf

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