SPIRIT demo case I: Full-scale on-site demonstration of a cascade industrial heat pump producing steam at 145°C

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Extended Abstract

Introduction

Industrial processes are currently responsible for 20% of the total greenhouse emissions in Europe [1]; heat pump technology can achieve a significant reduction of emissions arising from industrial heating by reusing industrial waste heat. A critical factor hindering the deployment of high-temperature heat pumps is the end-user hesitation to disrupt existing processes. This hesitation is partially inherent in capital-intensive industrial sites but also concerns the need for more operational experience. Therefore, the SPIRIT-HEU project aims to demonstrate industrial heat pumps at three different process sites with sink temperatures above 135°C; this will result in a double effect: (1) establishing end-user confidence in the technology and (2) ensuring the technology reaches TRL 7 [2].

Process and industrial heat pump description

One of the demonstrations within SPIRIT concerns the Stella Polaris plant. Stella Polaris is one of the world's leading producers of cold-water shrimp (annual production based on 15,000 metric tons of wild caught shrimp, frozen at sea) [3]. Production plants of cooked and peeled shrimp typically involve several stages of processing, including thawing, maturing, cooking, cooling, peeling, freezing and packaging. During these processes, heat flows are critical factors in maintaining the quality and safety of the product. The cooling duty during the refrigeration process is essential for maintaining the freshness and quality of the shrimp. The cooling is provided by a refrigeration system that uses ammonia as the refrigerant to absorb the heat from the shrimp and transfer it to the environment via seawater. On the other hand, the heat demand of the Stella Polaris plant is another critical factor in the overall process. Several processes require thermal energy: the shrimp cooker (steam), the air ventilation of the facility (hot water), and the cleaning of the factory (hot water). Currently, the process steam for the shrimp cooker is being supplied by a Propane boiler with a yearly fuel consumption of ~2,700 MWh, which results in emissions of ~600 tons of CO_2/year. A heat pump solution is proposed for the production of the steam for the shrimp cooker. The heat rejected from the refrigeration plant (ammonia cycle) was identified as the heat source for this heat pump.

This demonstration incorporates an industrial heat pump which upgrades the heat rejected from the shrimp freezing plant (~18°C) to produce steam (~145°C) for the cooking process. The heat produced by the heat pump will cover the full demand of the process under normal operating conditions (~700 kWth), thereby electrifying the process. The technology provider for this demonstration case is Mayekawa, an experienced manufacturer of customized heat pumps for a wide range of temperatures and capacities [4].

Due to the large temperature lift (> 130 K), a cascaded high-temperature heat pump was selected, consisting of an ammonia (bottom) cycle and a pentane (top) cycle. The two cycles are connected via a heat exchanger, specifically the condenser and evaporator of the ammonia and pentane cycle, respectively. The bottom cycle takes waste heat from the freezing plant while the top cycle produces the steam needed for the shrimp cooker. The process flow diagram of the heat pump and process are depicted in Figure 1.

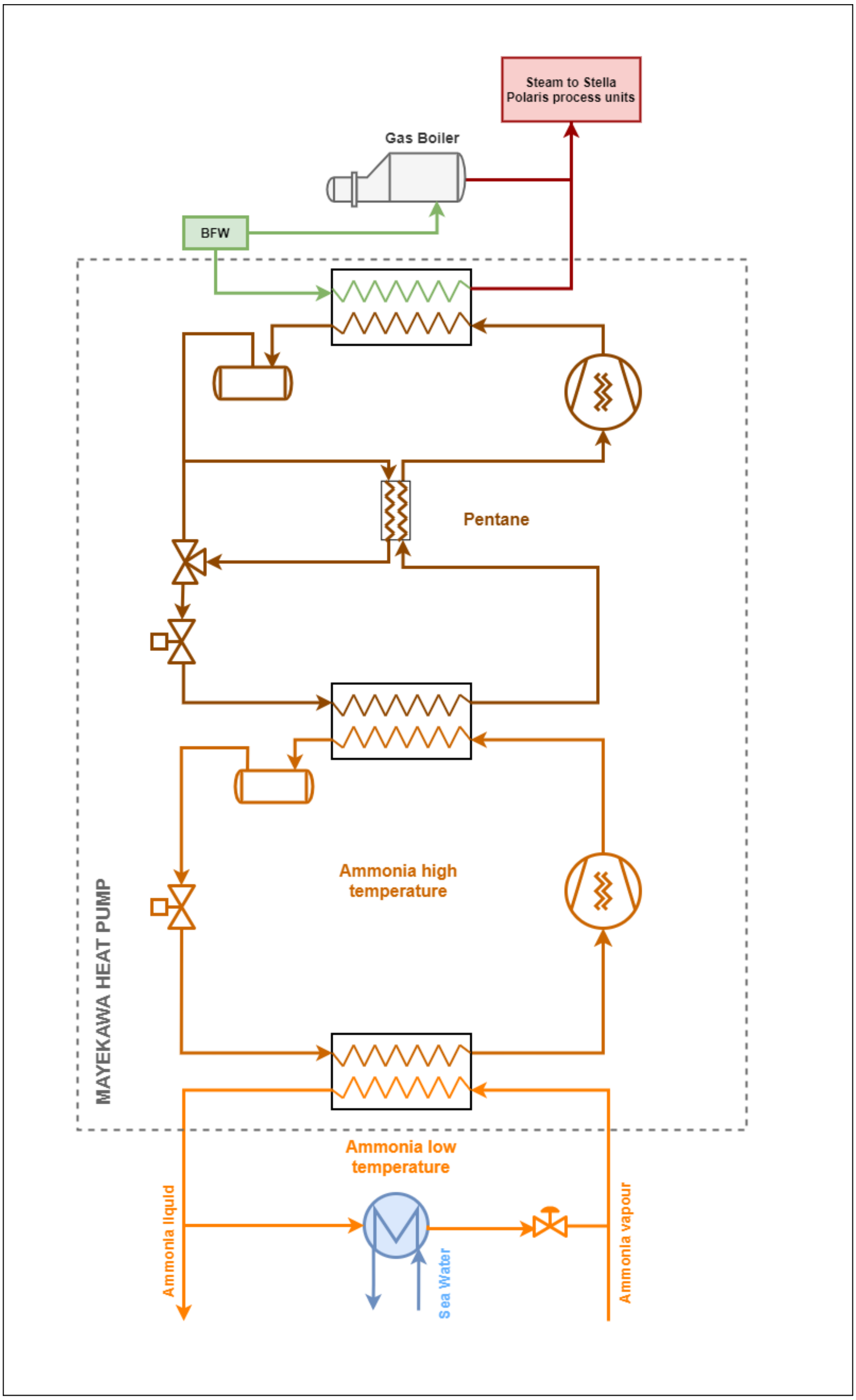

Figure 1: Process flow diagram of heat pump and process of Demonstration 1 of SPIRIT

Process modifications

The existing freezing shrimp plant of Stella Polaris consists of a single-stage ammonia system with economizers which provide cooling. The heat rejected by the condenser of the refrigeration plant, currently transfer to sea water, will be used as a waste heat source for the Mayekawa heat pump. Ammonia from the refrigeration plant condenses and provides the heat source by evaporating the ammonia of the bottom cycle of the Mayekawa heat pump.

The steam network takes fresh water and converts it into steam used in the shrimp cooker. The steam network will become an extension of the current system which utilises a propane boiler to produce steam. In order to electrify their system, Stella Polaris will install a steam electric boiler (e-boiler) to replace the propane boiler. The propane boiler will only serve as a backup if the e-boiler fails. Therefore, the steam network will have three distinct ways of producing steam with the following priority order: (1) via the heat pump, (2) via the e-boiler, and (3) via the propane boiler.

Heat pump design and performance

The bottom cycle takes waste heat from the freezing plant and upgrades it to an intermediate temperature level which can be utilized as source heat by the top cycle. Ammonia is used as the working fluid in this case to upgrade heat from 12°C to around 82°C. The evaporator is a flooded type, utilizing a shell and plate heat exchanger, with the evaporating medium in the shell side. It is condensed on the plate side of a shell and plate heat exchanger where heat is rejected to the top cycle.

The top cycle operates in a similar manner to the bottom cycle – this time Pentane is used as the working fluid due to its higher critical temperature and lower operating pressures. Heat from the bottom cycle is taken up in a shell and plate heat exchanger. The pentane is evaporated in a flooded system with the evaporation happening on the shell side of the heat exchanger. The evaporated pentane is superheated (using a IHX with the subcooling liquid pentane after the condenser) before being compressed by a screw compressor. The compressed gas is sent to a shell and plate heat exchanger where the pentane is condensed (plate side) and heat is rejected to produce steam (shell side). The condensed pentane is subcooled in the IHX before being expanded and returned to the flooded evaporator. On the steam network side the feed water flow is regulated by a level control valve and a pressure control valve at the outlet maintains the steam pressure constant. The compression process in the pentane heat pump is characterized by higher heat losses to the oil system compared to the ammonia compressor. A separate oil circuit significantly reduces losses compared with conventional lubricate screw compressors.

The expected Coefficient of performance (COP) of the heat pump is 1.8 and 2.5 for heating and combined heating/cooling, respectively. A one-dimensional steady-state model of the cascade heat pump was developed by TNO using Engineering equation solver (EES) [5]. The compressor is modelled using an approximation of the isentropic efficiency defined with data coming from Mayekawa. Moreover, the heat losses in the compressor to the oil are also accounted for using information from the Mayekawa. The thermodynamic model was used to check the initial sizing/performance of the cascade heat pump. Table 1 presents the expected overall performance of the cascaded heat pump, based on simulation data. Moreover, this information was also used to estimate the expected primary energy consumption and CO_2 savings with using an industrial heat pump instead of a Propane boiler: 1043 MWhr/year and 621 ton/year, respectively.

Table 1 Expected performance of the cascade heat pump, and of the individual cycles

Coefficient of Performance (COP)	Overall cascade heat pump	Ammonia heat pump (bottom cycle)	Pentane heat pump (top cycle)
COP heating	1.78	3.52	2.48
COP cooling	0.75	2.52	1.45
COP heating and cooling	2.53	6.04	3.92

Status of the design and implementation

As of the present stage, significant milestones in the development and modification of the industrial heat pump system and associated components have been achieved:

1. **Freezing plant modification:** The modifications required for the integration of the heat pump with the freezing plant have been successfully finalized. These alterations enable the redirection and utilization of waste heat, previously dissipated to seawater, as a key heat source for the industrial heat pump.
2. **Basic engineering of the heat pump:** The fundamental design and engineering phase of the industrial heat pump have been completed. This includes outlining the system's configuration, identifying/ordering key components, and determining the overall operational parameters required for effective functioning.
3. **Detailed engineering:** the project has completed the phase of detailed engineering, where intricate design elements and specifications are being further refined and developed. This phase involves a more comprehensive examination of various components, system integration, operational details, risk assessment, definition of the control narrative, among other.
4. **Order placement of major heat pump components:** Orders for the primary components of the industrial heat pump have been successfully placed (i.e., heat exchanger, compressor, etc). This crucial step secures the necessary equipment required for the construction and assembly of the heat pump system.
5. **Completion of detailed skid design:** The detailed design of the skid, which houses and supports the various components of the heat pump system, has been finalized. This aspect is essential for the efficient installation and integration of the heat pump within the existing industrial process infrastructure.
6. **Assembly:** the heat pump skid assembly is currently taking place at Mayekawa's workshop. The different components of the heat pumps (i.e., heat exchanger, compressor, valves, etc) are being integrated together.

Moving forward, the schedule and timeline for subsequent project phases have been outlined and agreed upon

- **Delivery:** The delivery of the heat pump skids, comprising of both heat pumps, is planned for April 2024.
- **Integration and Commissioning:** Post the successful integration of the heat pump with the process, the commissioning phase is scheduled to commence in August 2024. This critical stage involves fine-tuning to ensure optimal performance and functionality of the integrated system.
- **Experimental testing:** The testing of the industrial heat pump will consist of short and long-term testing. The short-term testing investigates part load operation and cycle parameter variations (i.e., compressor's oil temperature, external boundary conditions). The target of the long-term testing is for the heat pump to run more than 2,000 hours/year; the maximum operating hours of the process is around 3,600 hours/year. The aim is to investigate the variation in system performance over an extended time and determine the longevity of components, lubricant, and refrigerant under design conditions.

Conclusion

The SPIRIT-HEU project marks a significant stride in advancing the integration and utilization of industrial heat pumps within high-temperature processes, targeting a reduction in greenhouse gas emissions associated with industrial heating. The comprehensive demonstration of an industrial heat pump at Stella Polaris shrimp plant not only showcases the potential of heat pump technology but also addresses the crucial aspect of end-user confidence and TRL enhancement.

Overall, the project progresses in accordance with the established timeline, with essential components in place and detailed engineering completed for the heat pumps, signifying substantial strides towards achieving the project's objectives by the specified deadlines. If the demonstration is successful at Stella Polaris plant, then total primary energy consumption and CO_2 emissions will be reduced by approximately 1000 MWhr/Year and 600 ton/year, respectively.

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