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DECARBONISATION THROUGH INNOVATION

Design of a heat upgrade system for heat recovery in a paper factory

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Abstract

High-temperature heat pumps play a key role in industrial decarbonization by enabling the recovery and upgrading of waste heat to process-relevant temperatures. This paper presents the design of a heat upgrade system for a paper factory developed within the PUSH2HEAT project, demonstrating the industrial application of high-temperature heat pumps.

The system upgrades waste heat at 90 °C from a cogeneration plant to produce saturated process steam at 6.5 bar and 162 °C. Due to the high temperature lift, the process is implemented in two stages: a high-temperature heat pump with a screw compressor using R1233zd(E) generates steam at 1.7 bar (105 °C), followed by a mechanical vapor recompression unit that increases the steam pressure to 6.5 bar.

The non-flammable refrigerant enables direct steam generation in the condenser, eliminating the need for an intermediate heat exchanger. The condenser and evaporator are shell-and-tube type heat exchangers, with the refrigerant flowing in the tubes. The compressor for further vapor compression is lubricated with saturated water, which prevents oil contamination in the steam circuit and keeps the outlet temperature low.

At design conditions, the system recovers 600 kW, with electrical power of 143 kW and 149 kW required for the heat pump and vapor recompression stages, respectively, resulting in a heat pump COP of 5.2 and an overall system COP of 2.85.

Keywords: high temperature heat pump; heat recovery, mechanical vapor recompression, paper production;

1. Introduction

Decarbonizing industrial processes is critical to achieving global climate targets. The industrial sector accounts for around 24% of total energy-related greenhouse gas emissions [1] and 30% of final energy consumption worldwide [2]. In this context, waste heat recovery is increasingly recognized as a pivotal strategy for decarbonizing industrial processes. While estimating the actual magnitude of industrial waste heat is challenging, particularly for low-temperature streams, studies suggest that waste heat below 100 °C accounts for around 20% of global primary energy consumption. For the European Union, the total industrial waste heat potential is estimated at around 300 TWh/year. Of this, about one-third corresponds to temperatures below 200 °C, 25% in the range of 200-500 °C, and the remainder is above 500 °C. These figures highlight the vast, yet largely untapped, potential for waste heat recovery across various industrial sectors [3].

In energy-intensive industries, waste heat from processes is typically recovered where a potential use at a lower temperature is available. However, waste heat is often available at a temperature lower than that required by the process. Heat upgrade technology can bridge this temperature gap, and high-temperature heat pumps are the best alternative when waste heat availability is limited compared to the required process heat, or when it is comparable [4]. Numerous studies have demonstrated the suitability of high-temperature heat pumps for

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waste heat recovery in various industrial processes, including drying, sterilization, evaporation, papermaking and food preparation [5, 6].

Despite their potential, the adoption of HTHPs in high-temperature industrial applications remains limited, primarily due to technical challenges associated with achieving large temperature lifts and ensuring operational reliability[5]. The PUSH2HEAT [7] project addresses these gaps by developing four heat upgrade technologies and demonstrating them in four demo sites.

This paper focuses in one of the system developed for one of demonstration sites of the project, a paper factory of Cartiere di Guarcino, located central Italy. At first, the case study will be introduced, highlighting the temperature needs, the availability of waste heat and the current system layout. Then, the relevant design choices, such as system configuration, refrigerant selection, compressor technology, and system integration will be presented. Finally, the main energy and economic performance indicators will be presented.

2. Method

The heat upgrade system was designed to recover waste heat from the cooling water of a cogeneration plant, where the available thermal source is at 90 °C. The target was to produce saturated process steam at 6.5 bar (162 °C), which corresponds to the main steam collector of the plant. In this section the current plant layout, the waste heat availability and the requirements of the industrial site are first introduced. Then the developed solution is described, highlighting the features of the heat pump and of the entire heat upgrade system.

2.1. Site description and requirements.

The heat upgrade system presented in this work has been designed to meet the requirements of Cartiere Di Guarcino, a paper factory in Italy. The production plant consists of two paper machines enclosed within two warehouses, as shown in the upper part of Figure 1. The yearly electricity demand is 42 GWh, and 101 GWh of heat is required in the form of steam and hot water. The hot water is primarily used for space heating, with a small amount used for other domestic purposes. Steam is used in the paper production process; the two paper machines use 10 and 13 t per hour, respectively, of steam at 6.8 bar(a) when in operation.

The current energy system comprises two gas boilers and a CHP plant consisting of three 6 MW internal combustion engines. The steam produced by the engines and boilers is collected at the steam distribution site and distributed around the plant.

The CHP plant is fueled with biofuel and produces almost all of the required electrical energy; the excess production is delivered to the national grid. The CHP plant also produces 7-8 t/h of steam by recovering heat from the exhaust gases. Heat is also recovered from the engines' cooling water loop at around 90 °C.

The two gas boilers cover the remaining heating demand by producing steam at 14.5 bar(a), which is then throttled at a lower pressure according to demand.

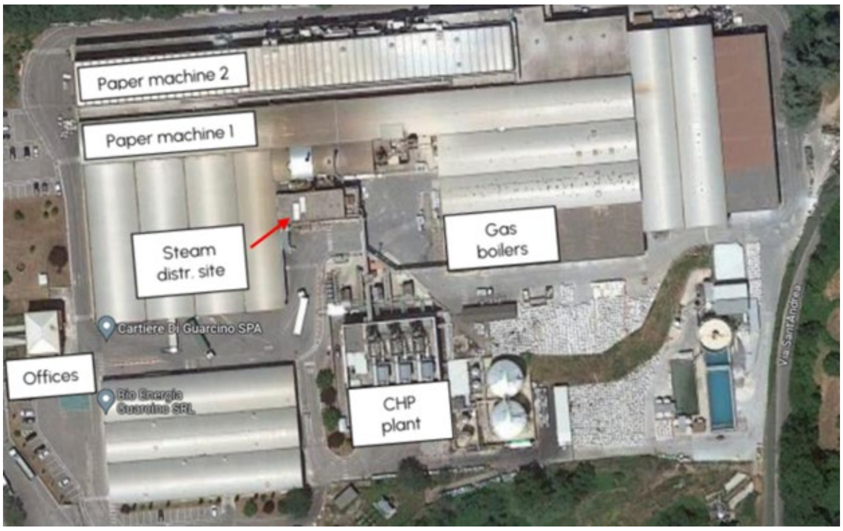

Figure 1. Layout of the CDG production plant.

2.2. Description of the new heat upgrade system.

The developed heat upgrade system consists of a high-temperature heat pump (HTHP) coupled with a mechanical vapor recompression (MVR) unit, as shown in Figure 2. Based on the required capacity and temperatures of the specific application considered, the combination of a screw-compressor heat pump with direct steam generation and an MVR system was identified as the most suitable solution in terms of performance and investment cost. The resulting system layout is presented in Figure 3, which also indicates the type and location of the sensors implemented for system monitoring.

The HTHP recovers approximately 600 kW_{th} from a hot water circuit at 90 °C, with a mass flow rate of 14.3 kg/s, supplied by the CHP plant. In the condenser, water from the deaerator at 105 °C and 1.7 bar(a) is preheated and evaporated, producing saturated steam at 115 °C. The MVR unit, lubricated with liquid water from the deaerator, is coupled to the HTHP to further compress the steam to 6.5 bar(a) and 162 °C.

The combined system operates continuously, with controlled pressures, temperatures, and flow rates to ensure efficient and reliable operation. The system's performance under the nominal conditions, as determined during the design phase, is summarized below:

- Heat delivered by the heat pump at the condenser: 743 kW
- Electrical power consumption of the heat pump compressor: 143 kW
- Heat pump coefficient of performance (COP): 5.2
- Total heat delivered to the steam header at 6.5 bar(a): 833 kWth
- Electrical power consumption of the MVR unit: 149 kW
- Overall system COP (HTHP + MVR): 2.85

2.3. Heat pump design

Cannon Bono developed a direct steam producing high-temperature heat pump utilizing a variable-speed twin screw compressor and R1233ZD as the working fluid. This refrigerant was selected for its non-flammability and compatibility with direct steam generation, thus eliminating the need for an intermediate heat exchanger and reducing safety risks associated with refrigerant leakage into the steam circuit.

The heat pump’s evaporator is a once trough type of heat exchanger with the refrigerant flowing inside tubes and the condenser kettle type of heat exchanger, with the refrigerant being on the tube side. These choices minimize the refrigerant volume needed for the system which will reduce the environmental risks in case of leakage. Waste heat is supplied to the evaporator at 600 kW, where it vaporises the refrigerant. The screw compressor then compresses the refrigerant vapour, raising its pressure and temperature to yield steam at 1.7 bar(a) (115 °C) on the shell side of the condenser.

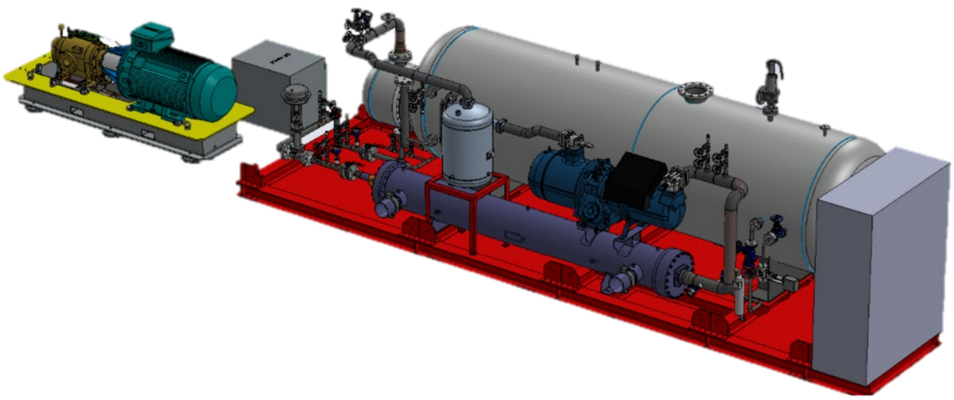

Figure 2. 3-D drawing of the heat upgrade system.

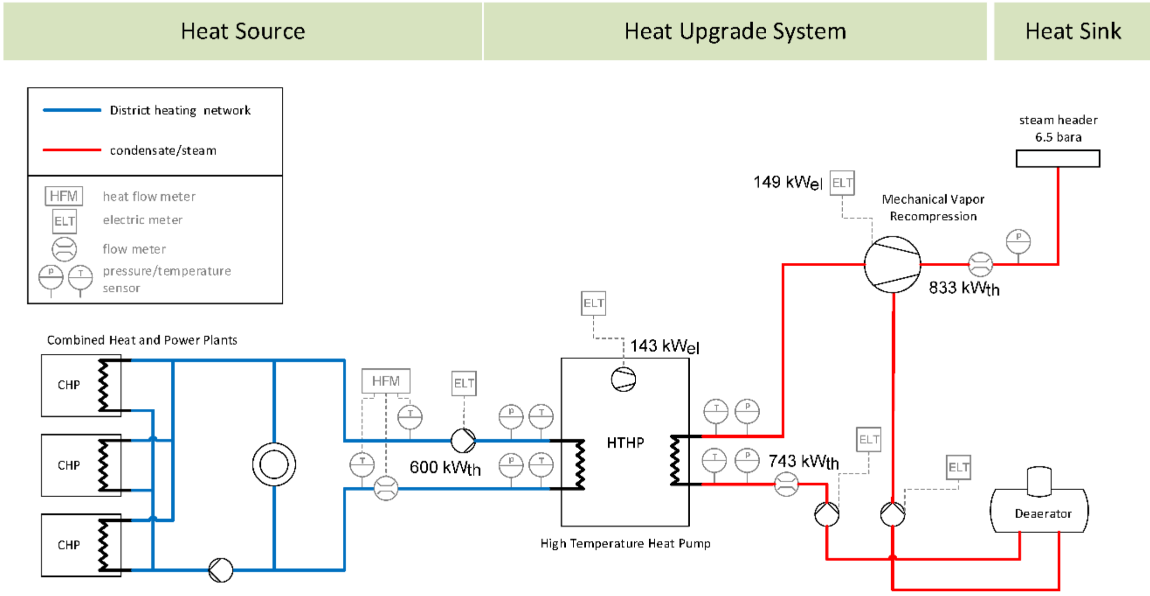

Figure 3. P&ID scheme of the heat upgrade system.

2.4. Selection of the MRV system

In the second stage, the generated steam is supplied to a mechanical vapor recompression unit. The compressor is lubricated with saturated water instead of oil, thereby avoiding oil contamination of the steam circuit and maintaining a low discharge temperature. As a consequence of this design choice, a two-phase mixture is formed at the compressor outlet, requiring a separator to ensure that only vapor is delivered to the process.

The energy content of the separated liquid water at 6.5 bar(a) is not included in the system COP calculation presented in Section 2.2. However, the potential use of this stream in the deaerator is currently under evaluation, as it could enable additional steam savings. If this contribution were recovered, the useful output of the heat upgrade system would increase by approximately 59 kW, bringing it to 892 kW and increasing the overall COP to 3.05. The intermediate pressure between the HTHP condenser and the MVR unit was determined by jointly analyzing the performance curves of both machines, with the objective of maximizing the overall system COP.

3. Energy and environmental analysis

This section presents the primary energy and CO_2 emissions savings that can be achieved thanks to the new heat upgrade system.

The calculation is based on the assumption that the system operates for 7 000 hours per year and that steam production reduces the load on the gas boilers. The efficiency of the gas boilers is assumed to remain constant at 0.85, based on the gross calorific value. This is a realistic assumption, given that the heat upgrade system has a smaller capacity than the boilers, meaning that the operation of the heat pump will not significantly affect the modulation range of the boilers.

The primary energy factors (PEF) associated with the electricity from the grid and the natural gas used in the CHP, along with the CO_2 emissions related to the two energy vectors, are reported in Table 1.

Table 1. Primary energy factor and CO_2 emissions for electricity and natural gas.

PEF	gas	1.05	MWh/MWh
	electricity	1.95	MWh/MWh
CO_2	gas	0.202	t/MWh$_{(LHV)}$
	electricity	0.357	t/MWh

With a capacity of 833 kW, the high temperature energy delivered by the heat upgrade system in one year is 5831 MWh. When comparing the base case conditions with the case with the new system in operation, the following variations can be calculated:

- Additional electrical energy demand for running the heat pump and the MVR system: 2046 MWh/y.
- Reduction in natural gas consumption for the boilers: 6860 MWh/y.

This translates in a reduction of the need of primary energy associated to natural gas of 7203 MWh/y and an increase of primary energy associated to electricity of 3990 MWh/y, with a net reduction of 3213 MWh/y.

Looking at the CO2 emissions, it is found a similar pattern, with 1386 t/y of reduction due to the lower natural gas consumption and an increase of 730 t/y due to the higher electricity needs, which lead to an overall savings of 655 t/y.

4. Conclusions

This work presented the development of a heat upgrade system for heat recovery in a paper factory within the PUSH2HEAT project. The proposed system integrates a high-temperature heat pump, which recovers heat from a cogeneration unit at 90 °C to generate steam at 1.7 bar(a), with a mechanical vapour recompression unit that further increases the steam pressure to 6.3 bar(a). Preliminary calculations show that the system could reduce primary energy by 3 213 MWh/y and CO_2 emissions by 655 t/y.

Following installation, the system will be monitored for a minimum of one year to evaluate its economic and environmental performance under real operating condition and to support system optimization and future improvements.

Acknowledgements

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