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Optimizing the Integration of Heat Pumps in Solvent Based Post-Combustion CO_2 Capture Plants

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Abstract

Although the chemical absorption method currently stands as the predominant approach for capturing CO_2 in industrial processes, its broader implementation is hindered by the process's energy penalties. This energy penalty mainly stems from the reboiler that uses steam, often produced from fossil fuels, to regenerate the solvent. This leads to additional CO_2 generation, which will either decrease the capture rate or will require to increase the capture plant capacity to process the additional flue gas. In this context, technologies allowing to produce decarbonized steam suitable for solvent regeneration looks particularly appealing. Heat pumps are key technologies in this perspective, which allows to recover waste heat and upgrade it to useful heat in many applications. Recently, with the expansion of their operating temperature ranges and their technological enhancements, the integration of high-temperature heat pumps poses a promising solution that can address the energy challenges in carbon capture plants. In fact, this application has been investigated in the literature. For instance, Zhang et al. explored the efficiency of a Monoethanolamine (MEA)-based carbon capture plant by recovering low-grade waste heat using different thermodynamic units, including an absorption heat pump (Zhang et al., 2023). The technologies were mainly utilized through cascade variations models which led to a notable decrease in energy consumption. Another promising study conducted by Alabdulkarem et al. investigated seven heat pump configurations along with forty-one different working fluids yielding an overall enhancement in the plant's efficiency (Alabdulkarem et al., 2015). The aforementioned studies, along with various others in the literature, achieved promising results; nevertheless, they highlighted the necessity for further optimization and the need for guidance in proper heat pump integration, laying the groundwork for future research endeavors.

For carbon capture in an industrial environment, each use-case exhibits a unique combination of a CO_2 capture unit characteristics with a given reboiler duty and temperature, a set of potentially valorizable heat sources within the CO_2 capture scope, a CO_2 conditioning section, and finally a set of waste heat sources from other nearby processes that could be advantageously utilized. This paper aims at illustrating, through the comparison of several heat pump implementation options, our current research aiming at developing a systematic methodology for highlighting the

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most relevant way to implement heat pumps for a given use-case.
In this study, the focus is made on mechanical compression type of heat pumps. Both closed-cycle compression heat pumps and open-cycle steam compression heat pumps (also called mechanical vapor recompression, MVR) are examined by the authors. The study strives to go beyond the basic heat pump cycle consisting of a single-stage compressor, a condenser, an expansion valve, and an evaporator, in order to improve the industrial relevancy of the proposed solutions. In the course of this research, the CESAR1 Aspen Plus model, developed by the Carbon Capture Simulation Initiative (CCSI) (Morgan et al., 2022), was upscaled and used. The reboiler has a heat demand of 55 MW (135°C/3.1 bara steam), and three waste heat sources candidate for valorization have been selected: the flue gas pretreatment unit, the regenerator's overhead condenser, and the CO_2 compression chain. Within the study, various heat pump architectures, including the pure refrigerant basic configuration, cascade heat pump configuration, and economizer heat pump, were modelled using Python. Different refrigerants, namely, Hydrofluro-Olefins (HFO), Hydrocarbons, and water (in MVRs) were considered. The use of water-based heat pumps is advantageous due to the benefit of enabling direct steam delivery to the reboiler. Finally, the possibility to implement a waterloop to harvest, transport and centralize the waste heat to a suitable location for implementing a large heat pump system has been also considered.

The study on the use-case examined three key aspects. First, it investigated the optimal heat pump architecture by comparing MVR-only configurations to MVR coupled with an advanced HFO or hydrocarbon cycle. Additionally, five different refrigerants in the HFO/hydrocarbon cycles were evaluated to determine which minimized exergy destruction. The results demonstrated that coupling an MVR with an economizer heat pump (containing an internal heat exchanger) was the most efficient configuration and that cyclopentane was the most suited refrigerant.

The second aspect of the study focused on maximizing the waste heat recovery potential of heat sources within the carbon capture plant. In particular, the CO_2 compression line was analyzed and assessed through various compression strategies, including wet and dry CO_2 compression, adjustments to the number of compression stages, and variations in intercooling. The specific conditions under which each strategy was most beneficial were identified.

The final part of the study integrated all previous results: the cycles were optimized and integrated into the carbon capture process.

The preliminary results obtained for a conventional CO_2 compression train (dry compression) are summarized below:

- Full Heat Coverage with MVR Alone:
  To cover 100% of the heat demand using only an MVR, a flash tank temperature as low as 65°C (0.25 bara) is required. While the achieved COP is promising (>4.4), this option seems to raise many challenges for an industrial implementation.

- MVR with a 1 bara Flash Tank Limit:
  If a pressure limit of 1 bara is imposed on the flash tank, to avoid vacuum conditions in the MVR suction line, only 33% of the heat requirement can be supplied, with a COP > 8.0.

- MVR Coupled with an Economizer Heat Pump:
  In this configuration, the MVR is coupled with closed-loop heat pump to supply 100% of the heat demand while avoiding an excessive vacuum operation. A waterloop is considered for simulating a case with a centralized heat pump. An economizer heat pump produces additional hot water to the flash tank, which operates at an optimized temperature of 85°C (0.6 bara) (see Figure 1). This setup results in an overall COP > 3.0.

These initial results illustrate the numerous possible tradeoffs in the implementation of heat pumps to efficiently generate decarbonized steam for amine-based CO_2 capture plants. It has been demonstrated that fulfilling the entire reboiler duty with heat pump systems, with the considered waste heat sources, is possible but raises some challenges. Also, the high COP of the second case suggest that a techno-economic optimum could be to only produce a portion of the reboiler duty with a MVR. The developed methodology is a powerful tool to systematically assess technical solutions for a given use-case and its available waste heat sources and provide valuable first insights about the impact of the selection of a given technological solution. Enhanced dry CO_2 compression scheme, tailored to generate heat with heat pump systems, wet CO_2 compression schemes enabling the optimal valorization of water latent heat as well as the availability of a waste heat source from a nearby process unit will be explored to provide additional insights about the potential of heat pumps to improve amine-based CO_2 capture units.

Keywords: Post-combustion; Amine CO2 capture, Heat pumps; MVR;System integration; Energy efficiency Optimization

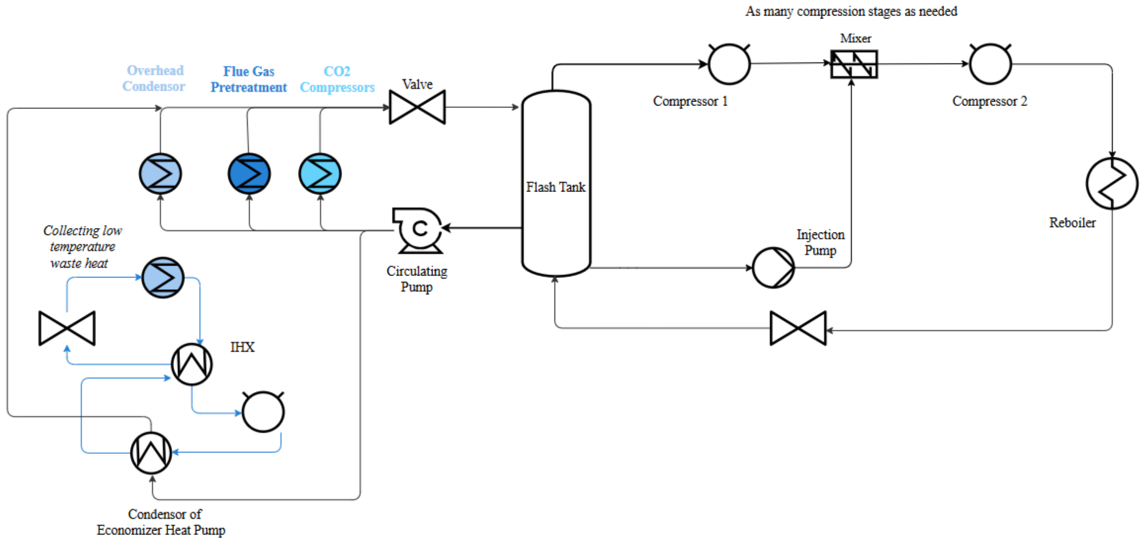

Figure 1: Schematic representation of the considered MVR system with a single Flash tank, allowing the use of an Economizer Heat Pump

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