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Integration of High-Temperature Heat Pumps for Steam Generation in Amine-Based CO_2 Capture: A Techno-economic Study

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Abstract

Amine-based CO_2 capture is a well-established process with numerous commercial-scale implementations worldwide and a high technology readiness level (TRL). Despite its maturity, the process remains highly energy-intensive, with the primary energy demand coming from the steam required for solvent regeneration. This dependence on steam not only increases operating costs but also contributes to indirect CO_2 emissions when steam is generated using fossil fuels. As industries seek to deploy carbon capture at scale, reducing the reliance on external steam in amine regeneration becomes a crucial challenge for improving both economic viability and environmental impact.

High-temperature heat pumps (HTHPs) present an opportunity to enhance process efficiency by upgrading waste heat within the system to produce the required steam. In this study, subcritical vapor compression heat pumps (closed-loop systems) are investigated both as standalone configurations and in combination with mechanical vapor recompression (MVR) to produce a target low pressure steam at 155°C. Two key waste heat sources in the process are considered: (1) the lean amine stream exiting the rich/lean heat exchanger, which is typically cooled before recirculation, and (2) the stripper overhead vapor, which is partially condensed to separate CO_2 product from the column's reflux stream. Additionally, an alternative configuration is examined for the latter where the stripper overhead vapor is first compressed before cooling, thereby increasing the stream's temperature and available heat.

The heat pump cycles are modelled in detail using Aspen HYSYS simulation software. Various cycle configurations are examined, including single-stage cycles, modified single-stage cycles incorporating internal heat exchangers (IHX) or economizers, and cascade, to improve the cycle performance based on the process requirements and the heat source conditions. The choice of refrigerant is another important design consideration for high temperature heat pumps. From a performance standpoint, such selection is constrained by the number of available refrigerants with no ozone depletion potential (ODP), global warming potential (GWP), toxicity, and flammability, that can be used in high temperature range. R-600 and R-601 are used as refrigerants in the current study, and their performance is compared against selected HFOs, and HCFOs in some of the configurations developed.

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Figure 1 presents the overall configuration of the following case studies:

- **Case 1**: combination of two single stage/economizer heat pump cycles on lean amine solvent and stripper overhead streams and a mechanical vapor recompression (MVR) system
- **Case 2**: a cascade heat pump cycle on compressed stripper overhead stream

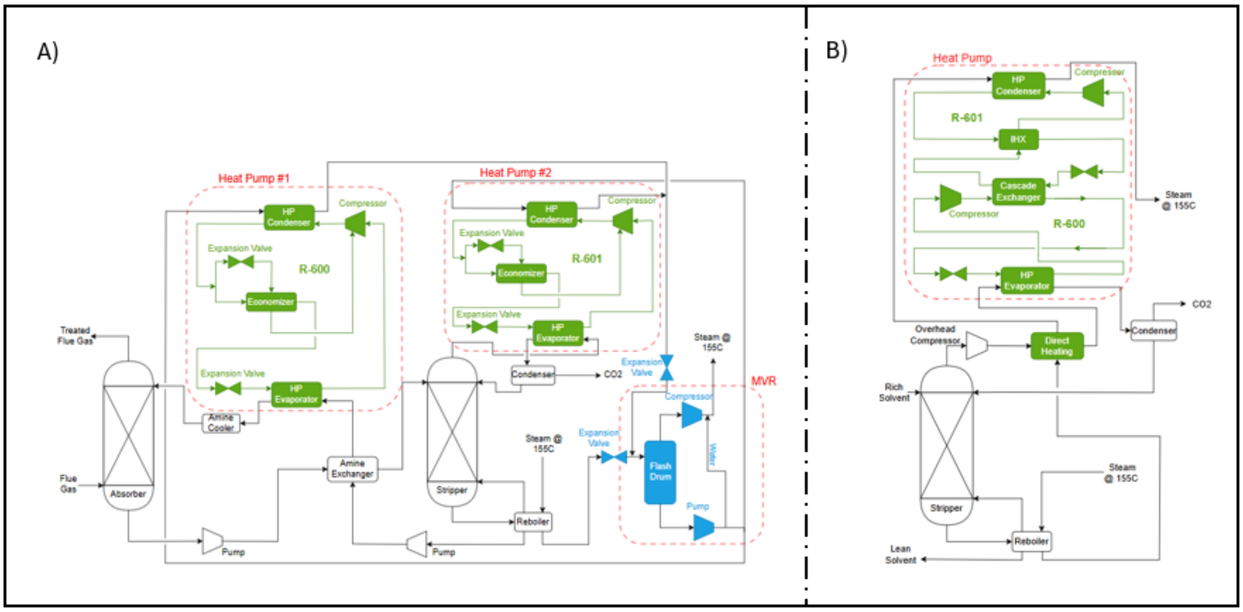

Figure 1: Simplified diagram of heat pump configurations applied in amine-based CO_2 capture process:
A) Case 1: two single-stage with economizer cycles combined with MVR.
B) Case 2: one single cascade cycle on compressed stripper overhead stream.

The design parameters in both cases are set in a way that they can produce the total amount of steam required by the capture unit. The main performance indicators of the heat pump cycles are presented in Table 1 highlighting key trade-offs in implementation, efficiency and electricity demand. Case 1 integrates a combination of heat pump cycles and mechanical vapor recompression (MVR), which results in a lower electricity consumption of 240 kWh per tonne of steam produced. This is due to the lower temperature lift required in the heat pump cycles, leading to a higher coefficient of performance (COP) compared to Case 2. In contrast, Case 2 directly produces the target steam at 155°C from a single heat source using a cascade heat pump configuration. While this eliminates the need for MVR, it requires a higher condensation temperature and a greater overall temperature lift, leading to a lower COP and a higher electricity demand of 279 kWh per tonne of steam. Furthermore, since Case 2 utilizes the compressed stripper overhead stream as a heat source, the total electricity demand increases further to 348 kWh per tonne of steam when accounting for the additional power required for the stripper overhead compressor. However, Case 2 offers an advantage when a CO_2 compression section is included downstream of the capture process, as it delivers CO_2 at a higher pressure, potentially reducing the cost and energy requirements of the compression system.

Table 1: Performance summary of heat pump cases presented in Figure 1

Parameter	**Case 1**			**Case 2**	
Cycle configuration	Single stage with economizer	Single stage with economizer	MVR	Cascade	
Heat source	Lean Amine Solvent	Stripper Overhead Stream	-	Compressed Stripper Overhead Stream	
Refrigerant	R-600	R-601	R-718	R-600	R-601
Evaporation/condensation temperature, °C	40 / 130	64 / 130	-	37 / 100	90 / 164

Pressure ratio	7.0	4.6	3.5	4.4	4.3
COP	2.7	4.2	4.2	1.9	
Power demand, kWh/tonne steam	240			279 (without SOC*) 348 (with SOC)	

* SOC: stripper overhead compression

In terms of cost, both cases increase the CO_2 capture cost compared to the conventional process, with Case 2 resulting in a more significant increase. If a compression section is added downstream of the capture unit to compress the CO_2 to the pressure required for pipeline transportation or further utilization, the total costs increase further across all cases. However, the additional cost for Case 2 is less pronounced since the stripper overhead compressor contributes to the CO_2 compression system. Ultimately, the choice between configurations depends on the trade-off between steam generation efficiency, the complexity of the system, the investment costs associated with each case, and the benefits of lower CO_2 compression costs.

Keywords: high-temperature heat pump; process electrification, Aspen HYSYS; CO_2 capture; process modeling;waste heat recovery; mechanical vapor recompression, cost estimation