Research Article - Peer Reviewed Conference Proceeding
ESCAPE 35 - European Symposium on Computer Aided Process Engineering
Ghent, Belgium. 6-9 July 2025
Jan F.M. Van Impe, Grégoire Léonard, Satyajeet S. Bhonsale,
Monika E. Polańska, Filip Logist (Eds.)

Thermodynamic Feasibility of High-Temperature Heat Pumps in CO_2 Capture Systems

Brieuc Beguin* and Grégoire Léonard

University of Liège, Department of Chemical Engineering, Liège, Belgium
* Corresponding Author: brieuc.beguin@uliege.be.

ABSTRACT

The feasibility of integrating a closed-loop, high-temperature heat pump into an MEA-based CO_2 capture system is investigated using well-established process integration methods. The performance of reversible heat pumps is evaluated, showing promising results (15% savings of exergy), which encourage further development and extension towards realistic cycles.

Keywords: Carbon Capture, High-Temperature Heat Pump, Exergy, Process Intensification

INTRODUCTION

To address the high energy consumption of amine-based CO_2 capture systems, integrating high-temperature heat pumps could be interesting, given the availability of waste heat [1]. This paper explores the possibilities of implementing a closed-loop heat pump, by focusing on what thermodynamics allows and therefore identifying the limits of such an integration.

METHODOLOGY

Pinch Analysis is used to generate the Grand Composite Curve of the process and identify the pinch point. Heat pump integration is studied by optimising the operation scheme between the cold region below the pinch point and the hot region above it.

As an extension of Pinch Analysis to distillation columns, Dhole and Linnhoff [2] proposed a Column Grand Composite Curve (CGCC) to compare actual operation to that of an ideal column (at Minimum Thermodynamic Condition). It illustrates the ideal heat supply distribution along the column. Interpreting a CGCC helps identify opportunities for side reboiling, at a lower temperature.

Both concepts are applied to a converged simulation of an MEA-based system that captures 90% of the CO_2 emissions from a 12 MW biomass boiler.

RESULTS

Figure 1 shows the GCC of the base system. There is limited internal heat integration potential, with a single self-sufficient ‘pocket’ (in yellow). This pocket is highly dependent on the compression train, which in this case study compresses CO_2 to 20 bar. Supplying the remaining 4295 kW of heat with a reversible heat pump (e.g. Carnot cycle) would require raising all available waste heat at 45°C to above the pinch point temperature. The heat pump would consume 967 kW (COP_{Carnot} = 4.44). The performance of a real heat pump would be lower.

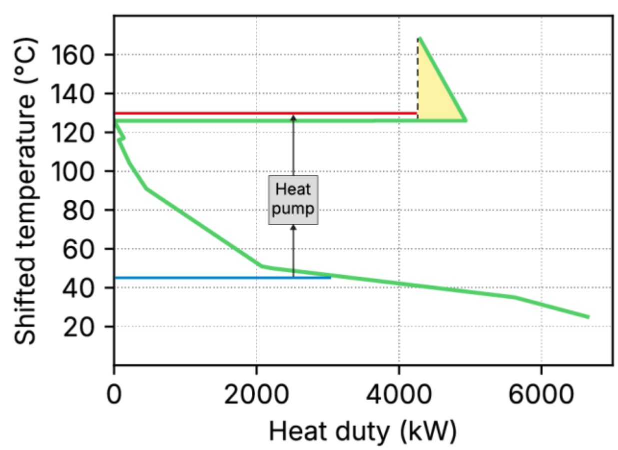

Figure 1. GCC of the base system (green) and optimal reversible heat pump system that replaces the reboiler.

Instead of completely replacing the reboiler, one could attempt to relieve it from some of its heat demand. In addition, treating the column and its reboiler as a single stream hides the fact that not all heat must be supplied at the maximum temperature. Instead, one could use the CGCC to identify at which intermediate temperature, lower than that of the reboiler, the heat pump could supply heat without affecting the capture rate.

Typically, CGCCs are represented as a temperature-enthalpy profile. However, as both heat and electricity are involved, it is relevant to use exergy as a common basis for comparison. Exergy flows with heat ($\dot{X}$) can be calculated by multiplying the heat flow rate ($\dot{Q}$, at a temperature T) by the Carnot factor (with the reference temperature $T_0 = 298.15\ K$):

$$\dot{X} = \dot{Q}\left(1 - \frac{T_0}{T}\right) \quad (1)$$

Thus, the Carnot factor can be used as an axis instead of temperature. With this representation, the area under the curve is equal to the exergy transfer to the column. The optimal side reboiler placement is then determined by minimizing the hashed area in Figure 2. The CGCC indicates an optimal heat supply of 1347 kW at a temperature of 108°C.

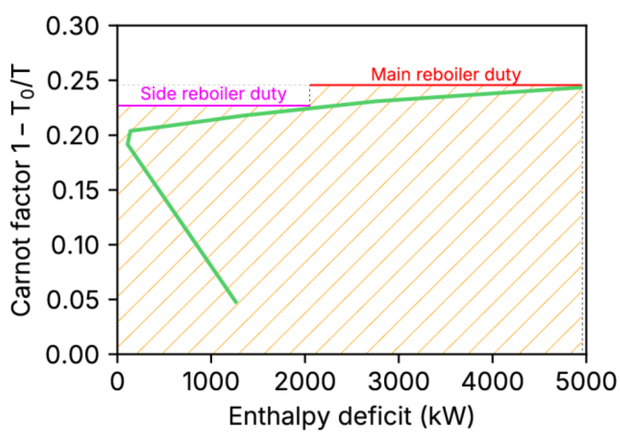

Figure 2. CGCC of the stripper (green) and example of the exergy calculation with a side reboiler (hashed area).

The heat pump could be used exclusively to supply this side reboiler. The simulation is modified accordingly by adding a corresponding heat stream to the stage closest in temperature to the optimal value. The optimal heat pump (i.e. with the lower temperature lift, considering the availability of waste heat at different temperatures) is determined similarly to the base system's GCC. Figure 3 illustrates the result, showing the waste heat source at 73°C. The corresponding heat pump requires 162 kW of electricity (COP_{Carnot} = 8.31).

When simulating the capture system combined with this heat pump, column temperatures increase, and the total heat demand increases, although it is distributed between two temperatures. However, since part of the heat is recycled and cold utility is reduced, the exergy consumption of the process decreases by 15.3%.

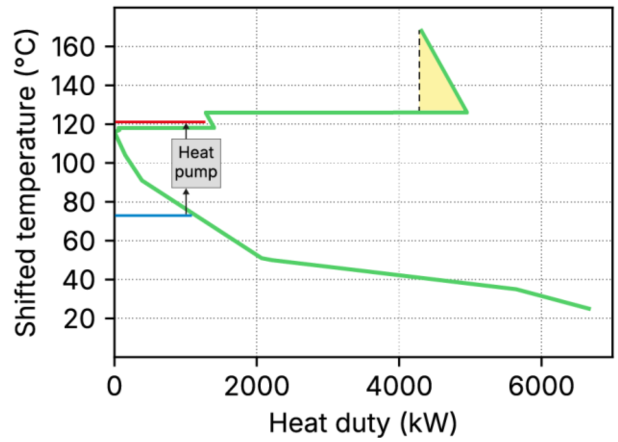

Figure 3. New GCC (green) and optimal heat pump.

CONCLUSION

Integrating a high-temperature heat pump into an amine-based CO_2 capture system is thermodynamically feasible. The reported gains are encouraging but should be translated to non-ideal processes. Other heat integration techniques could expand the possibilities [3]. Adjusting the stripper's pressure – which affects the temperature – could also bring additional benefits [1], as could other types of heat pumps, such as Mechanical Vapour Recompression. Economic evaluations are also essential to assess the practical feasibility of such systems.

ACKNOWLEDGEMENTS

This publication is supported by the Walloon Region through a FRIA grant.

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