OPTIMAL INTEGRATION OF A HIGH-TEMPERATURE HEAT PUMP IN A CO_2 CAPTURE PILOT PLANT

Brieuc Beguin*, Théo Van Lierop, Grégoire Léonard

University of Liège, Department of Chemical Engineering, Liège, Belgium

* *Corresponding Author:* brieuc.beguin@uliege.be

Abstract. This study investigates the integration of a high-temperature heat pump into a CO_2 capture process within a 1-tonne-per-day carbon capture pilot plant, designed to separate CO_2 from the flue gases of an industrial biomass boiler by the means of an absorption-regeneration solvent loop. The operating pressure of the solvent regeneration unit (stripping column) was optimised as a trade-off between the increased reboiler heat duty and the decreased temperature lift as pressure decreased. A single-stage heat pump was initially tested and, although it could not totally replace the reboiler, it reduced total electricity consumption. A two-stage configuration was then explored, with the intermediate evaporator optimised to recover heat from the stripper overhead condenser at an optimal temperature. Final results showed that the best achievable reduction in electricity consumption reached 73%, but stagnated below 80 kPa due to increased CO_2 compressor consumption. These findings suggest that a fully electrified CO_2 capture process is feasible and should ideally operate at or below atmospheric pressure for optimal energy efficiency.

Keywords. CO_2 capture, High-temperature heat pump, Heat integration

1 Introduction

Over the past two decades, CO_2 capture has gained momentum as a tool both for carbon dioxide removal (CDR) and for the mitigation of hard-to-abate emissions. Amine-based chemical absorption stands out as the most mature technology, with large-scale industrial applications already in operation [1].

This process relies on the selective absorption of CO_2 from gaseous streams by a chemical solvent, most commonly 30 wt-% monoethanolamine (MEA) in water. At first, the gaseous stream and the aqueous solvent are brought in contact with each other in an absorption column and the solvent becomes loaded with CO_2 as it is removed from the gaseous stream. The loaded solvent is then regenerated in a stripping column using thermal energy. This heat consumption remains the largest challenge of the technology. To limit its burden, researchers are developing alternative solvents, process modifications, and heat integration techniques.

The source of thermal energy varies depending on the host process, with steam extraction preferred when feasible. In cases where on-site steam is unavailable, electricity may be an alternative carrier, particularly for pilot plants where versatility and simplicity are essential. Heat pumping is a sensible way to electrify the process and many configurations based on a heat pumping effect are proposed in the scientific literature [2]. However, the sole dependency on a heat pump to sustain the energy consumption of the whole system is a more recent research area. Jensen *et al*. [3] have proposed using a high-temperature heat pump in such scenarios, applying their electrification approach to a biogas upgrading plant.

Within the MEA-based CO_2 capture process, operating parameters can be adjusted to minimise energy requirements. One of these variables is the stripper pressure: higher pressures reduce the specific reboiler heat duty (SRD) [4]. The marginal gains tend to decrease, and a techno-economic optimum can be found, accounting for additional equipment and pumping costs. However, higher stripper pressures have a side effect that conflicts with heat pump integration: as pressure rises, so does the reboiler temperature. This increases the temperature lift that the heat pump must achieve, thereby reducing its performance.

This study extends the proposed methodology by Jensen *et al.* [3] to another case study, analysing both the optimal stripper pressure and the optimal waste heat temperature level. Basic heat pump architectures are tested, and total electricity consumption is compared.

2 Case study

A 1-tonne-per-day carbon capture pilot plant currently in development at the University of Liège, Belgium, is used as the case study. It separates CO_2 from the flue gases of an industrial biomass cogeneration plant. Because it is designed to be mobile, the pilot's heat requirements are met by electric heaters and waste heat can only be recovered from within the capture process. The challenge is therefore to minimise the electricity consumption by efficient internal heat recovery.

The pilot is modelled in Aspen Plus V14, with the base design setting the stripper pressure at 200 kPa (absolute). The corresponding energy requirement amounts to 3.28 MJ/kgCO_2, or 37.94 kW. Waste heat is available at different temperature levels, with most of it at 40°C. However, the stripper overhead condenser (SOC), which condenses water vapour to separate it from CO_2 at the top of the stripper, operates at a higher temperature, releasing 8.37 kW as it cools the stream from 94°C to 40°C. As illustrated in Figure 1, this partial condenser has a concave temperature-enthalpy (T-Q) diagram, allowing the recovery of a larger amount of waste heat at any temperature level compared to the linear T-Q curve of a conventional heat exchanger.

Regarding the heat pump, preliminary studies have identified R1233zd(E) as the heat pump working fluid for its safety, its critical temperature (165.5°C), and its low environmental impact [5].

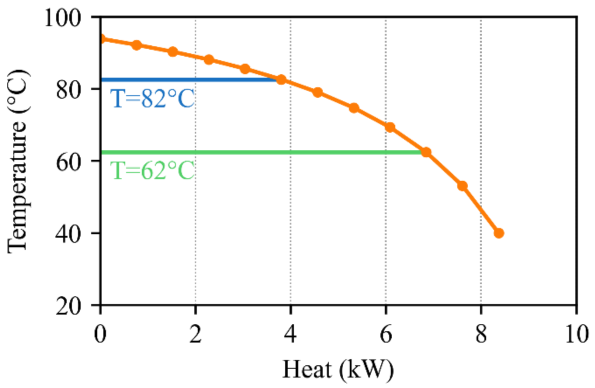

Figure 1: T-Q curve of the SOC at 200 kPa. The blue and green lines are examples of waste heat recovery potentials at two different temperatures.

3 Methodology

The Aspen Plus model is sized to achieve the target capture capacity of 1 tonne CO_2 per day. Simulations are conducted for 18 stripper pressure levels ranging from 30 kPa to 500 kPa. In every simulation, the captured CO_2 is compressed to 500 kPa to allow for a fair comparison. For each pressure level, temperature profiles, reboiler duty, and T-Q curves are generated and saved as inputs for the heat pump model.

The heat pump is modelled in Engineering Equation Solver (EES). Compressor power consumption is calculated with an assumed isentropic efficiency of 0.85 and a motor efficiency of 0.8. Heat exchangers are set with a pinch point temperature difference of 5 K.

At first, a single-stage architecture is simulated. The heat pump draws all available heat from the SOC to relieve the electric reboiler. This option ensures compacity, low complexity and low costs, which are all relevant for a pilot plant.

Then, a two-stage architecture is implemented. The electric reboiler is entirely replaced by the heat pump condenser while two evaporators are used to recover waste heat. The first evaporator draws heat from the SOC and individual simulations based on a 12-point discretisation of the T-Q curve are performed to identify the optimal operating temperature. Figure 1 illustrates two example points, showing the heat recovery potential when the stripper pressure is set to 200 kPa. The second evaporator supplies the remaining required power by extracting heat from an unlimited source at 40°C, representing the aggregate of other waste heat sources within the process. This lowest temperature is a strict constraint to which all streams are cooled as they leave the system to maintain the water balance. Limitations on the amount of heat that can be extracted from this low-temperature source are discussed in the next section. Total power consumption of the coupled CO_2 capture and heat pump system is then compared across all simulations.

4 Results and discussion

Figure 2 shows the influence of stripper pressure on both reboiler heat duty and temperature. The opposing trends in these variables appear clearly. On a side note, it is interesting to note that reboiler temperature impacts solvent degradation, with higher temperatures leading to increased degradation [6], [7]. Future works could extend the capture model to account for this phenomenon, and degradation product concentrations could be monitored for each pressure level.

Simulations results from the single-stage heat pump show that for any stripper pressure, waste heat availability in the SOC alone is insufficient to replace the reboiler, regardless of the waste heat temperature level. An electric boiler is still required for a fraction of the power. Therefore, the minimum electricity consumption is achieved when the heat pump operates at the lowest possible waste heat temperature (40°C) as it allows for the recovery of the largest amount of heat.

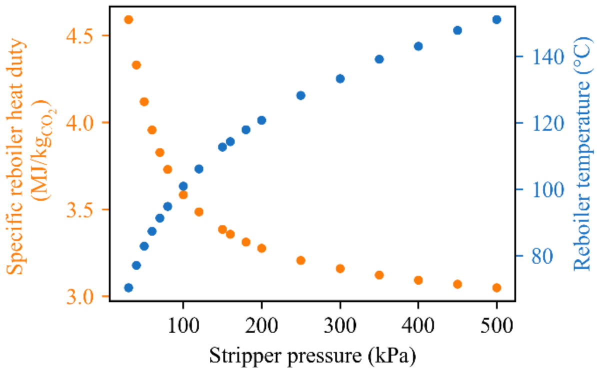

Figure 2: Influence of the stripper pressure on the reboiler heat duty and the reboiler temperature.

In the two-stage configuration, electricity consumption reaches a minimum at an intermediate waste heat temperature level in the SOC, as illustrated in Figure 3. This entails that this intermediate temperature achieves a higher COP, even though not all available waste heat is extracted. While the SOC temperature range varies with pressure, the optimal temperature appears to lie consistently a few degrees below the midpoint of the range. Further studies could provide insights into this trend.

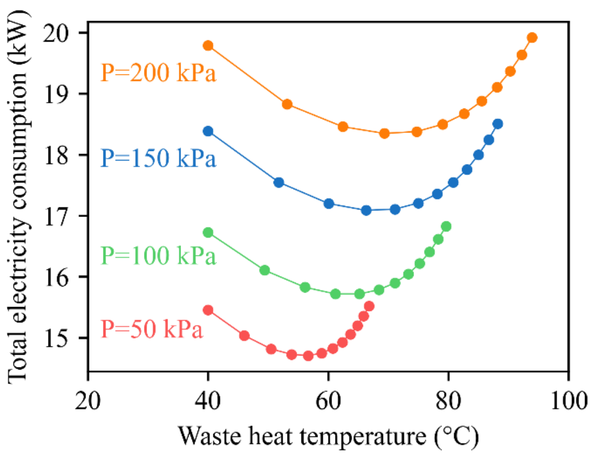

Figure 3: Optimal waste heat temperature.

Figure 4 depicts the total energy consumption for each of the 18 stripper pressure levels. The blue dot represents the base case consumption, *i.e.* before heat pump integration when electric heaters supplied the heat. For all investigated pressures, integrating the heat pump reduces the total electricity consumption. The savings range from 23% of the initial electricity consumption to a maximum of 73%.

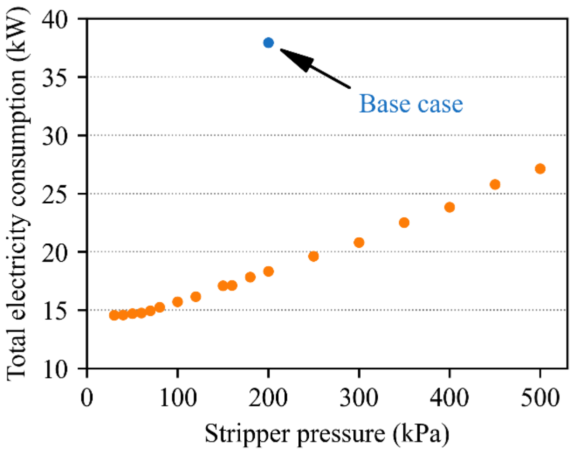

Figure 4: Total electricity consumption of the pilot plant for different stripper pressures.

The benefits of a lower temperature lift outweigh the increase in reboiler heat duty. High-pressure strippers, in addition to the increased risk of solvent degradation [6], appear suboptimal for integrated electrified CO_2 capture systems.

Given the scale of the pilot plant, solvent pumping is a negligeable contribution to the total electricity consumption. Instead, the electricity consumption is divided between the heat pump and the CO_2 compressor, with the compressor accounting for under 1% at 450 kPa, 5% at 200 kPa, 13% at 100 kPa, and 34% at 30 kPa. As the stripper pressure decreases, the compressor's electricity consumption increases, causing the benefits of a low temperature lift start to fade at lower pressures as the total electricity consumption stagnates from around 80 kPa. The consumption increase at the lowest pressures identified by Jensen *et al.* [3] does not appear in the present results. This implies that vacuum-operated strippers (VOS) may only bring marginal benefits and that operating the stripper at atmospheric pressure could be a satisfying balance. A finer analysis is necessary to clarify the total consumption behaviour in vacuum-operated strippers.

Lastly, the lack of constraints on the second evaporator (the unlimited, low-temperature heat source at 40°C) has not compromised the results, as the extracted heat remains below the total available waste heat at the respective temperature across all simulations.

5 Conclusions

A high-temperature heat pump was modelled and integrated into a CO_2 capture pilot plant.

Initially, a single-stage configuration was tested to extract waste heat from the stripper overhead condenser, which is the nearest available source. Results indicated that while this configuration could not fully replace the reboiler, it did reduce the overall electricity consumption.

Next, a two-stage heat pump was evaluated. The intermediate evaporator extracted heat from a source with a large temperature glide (94°C to 40°C) and the second drew heat from an additional source at 40°C. The temperature level of the intermediate evaporator was optimised according to heat availability. With an increasing CO_2 compressor consumption at lower pressure levels, the reduction of total consumption stalled from 80 kPa downwards with an energy saving of 73% compared to the base case.

Integrating a high-temperature heat pump to electrify the CO_2 capture process is possible and leads to a substantial reduction in electricity consumption. To maximise these benefits, it is advised to go against the high-pressure stripper trend and instead design atmospheric or vacuum-operated strippers.

The present work was conducted on a small-scale pilot plant. However, there is no indication that these conclusions would degrade if the system were scaled up. In fact, applying the methodology to a full-scale plant, along with its host process, could reveal additional opportunities for heat integration as more waste heat sources would be available.

Exploring alternative heat pump configuration beyond the basic two-stage heat pump architecture could further expand the integration analysis. Introducing internal heat exchangers, flash tanks, vapour injection, and other components could bring down the energy consumption, at the expense of complexity. Testing alternative refrigerants could also be valuable.

It should also be noted that a closed-loop heat pump may not be the most optimal way to integrate a vapour compression system into the carbon capture process. A more comprehensive analysis of the entire system's heat integration is needed. A pinch analysis would be an essential first step in that direction.

Finally, because heat pump performance decreases under part-load conditions, it would be relevant to extend the present work to an hourly study of the system. This would allow for the study of transient operation and the resulting heat pump performance. Relying solely on nominal power simulation results may be unrealistic and may yield overly optimistic performance estimates.

Acknowledgement

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

References

[1] M. Bui et al., 'Carbon capture and storage (CCS): the way forward', Energy Environ. Sci., vol. 11, no. 5, pp. 1062–1176, 2018.

[2] Y. Le Moullec et al., 'Process modifications for solvent-based post-combustion CO_2 capture', Int. J. Greenh. Gas Control, vol. 31, pp. 96–112, 2014.

[3] E. H. Jensen et al., 'Electrification of amine-based CO_2 capture utilizing heat pumps', Carbon Capture Sci. Technol., vol. 10, p. 100154, 2024.

[4] G. Léonard, et al., 'Influence of process operating conditions on solvent thermal and oxidative degradation in post-combustion CO_2 capture', Comput. Chem. Eng., vol. 83, pp. 121–130, 2015.

[5] C. Arpagaus et al., 'High temperature heat pump using HFO and HCFO refrigerants - System design, simulation, and first experimental results', International Refrigeration and Air Conditioning Conference, Purdue, USA, 2018.

[6] S. S. Warudkar et al., 'Influence of stripper operating parameters on the performance of amine absorption systems for post-combustion carbon capture: Part I. High pressure strippers', Int. J. Greenh. Gas Control, vol. 16, pp. 342–350, 2013.

[7] J. Davis and G. Rochelle, 'Thermal degradation of monoethanolamine at stripper conditions', Energy Procedia, vol. 1, no. 1, pp. 327–333, 2009.