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Optimizing CO_2 capture efficiency: integrating high temperature heat pumps to achieve 60% final energy reduction

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Abstract

This paper concerns a study on reducing the energy demand of an amine based CO_2-capture process by applying a heat pump to this process. This work is part of the HEU project HiRECORD which aims to reduce the costs of CO_2-capture. Applying a heat pump to the capture process allows for recovery and upgrading of waste heat within the system, therewith reducing the net energy demand and energy costs of operating this process. The target for final energy reduction was set at 60%. This translates to a required Coefficient of Performance (COP) for the heat pump of 2.5. Thermodynamic calculations have been carried out combining several waste heat sources within the process with the required heat demand of 130°C for the reboiler of the regeneration column. Data from a CO_2 capture plant at a quick lime production plant, with a capture rate of 5.6 ton/h, has been used as input. The modelling work resulted in a heat pump concept with two parallel compressors, each using a different combination of waste heat sources from within the capture process. Isopentane (R601a) was selected as the working medium and an assessment was made on the availability of commercially available compressors for this heat pump. The required compressor properties with respect to pressure ratio and volume flow fit very well within existing compressors. The calculated COP is 2.76, meeting the target of the project. The specific regeneration energy of the CO_2 capture plant is reduced from 3.29 GJth/ton to 1.29 GJel/ton, allowing for significant operational cost savings.

Keywords: High-temperature heat pump; heat integration; CO_2 capture; energy recovery; industrial decarbonization

1. Introduction

Global efforts to mitigate climate change have placed significant emphasis on reducing CO_2 emissions from industrial sources. Industries such as cement, steel, and quicklime production are considered hard-to-abate sectors due to the inherent process emissions that cannot be eliminated through fuel switching alone. CO_2 capture from flue gases has emerged as a critical technology for these sectors. Compared to other capture technologies, solvent-based CO_2 capture is the most mature technology and the one with the highest potential for short-term deployment. Despite the progress made in the past, significant reductions are still necessary in both capital and operational capture costs, to accelerate implementation of capture plants in industry.

The HiRECORD HEU project applies Rotating Packed Bed (RPB) technology, which will enable smaller equipment footprints and therewith reduce capital costs. The technology is also more efficient than conventional technologies, leading to lower operational costs [1]. This technology will be piloted within HiRECORD at 3 industrial sites. The energy efficiency of the overall system is improved by this study, which analyses the integration of a high-temperature heat pump within the capture process. The heat pump recovers and upgrades waste heat from the capture and compression processes, thereby reducing the overall energy demand. This manuscript explores the methodology, design considerations, and performance outcomes of such integration, aiming to meet the ambitious target of 60% final energy reduction.

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2. Approach

The heat pump integration study has been applied to a full-scale CO_2 capture system at a quicklime plant of CaO Hellas, which is one of the sites where the capture technology will be piloted. The capture system is designed to capture 5.6 ton CO_2/h. The process flow diagram of the capture process is depicted in Figure 1. In addition, there is a compression train to bring the pressure of CO_2 up to the required 150 barg for transport. This compression train has several intercoolers to prevent temperature limitations of the compressors involved.

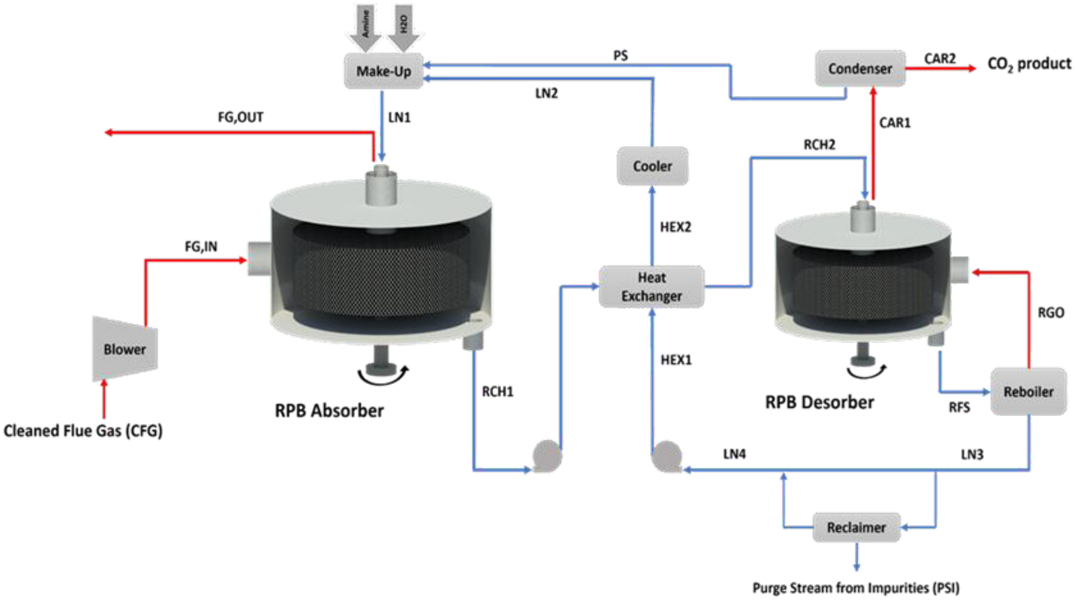

Figure 1 Process flow diagram of the CO_2 capture process

The capture process requires a thermal energy input of 5153 kW in the reboiler of the RPB desorber at a temperature level of 120 °C. Steam of 125 °C (1.3 barg) is used to supply this heat. This heat will be provided by a heat pump that makes use of available waste heat sources within the carbon capture process. These sources are as follows: (1) the overhead condenser of the RPB desorber, (2) the lean solvent cooler, and (3) the interstage coolers of the CO_2 compression train. An additional possible heat source is the oil cooler of the heat pump system. The duties and temperature of both heat sources and sink are given in Table 1. The underlying model that has calculated this data is described in [2]. It must be mentioned that the duty of the condenser also involves condensation of water. This stream contains both sensible and latent heat.

Table 1 Duties and temperatures of waste heat sources and heat sink of the heat pump

#	Duty [kW]	Temperature in [°C]	Temperature out [°C]
Reboiler	5152.6	120.0	120.0
Condenser	-1792.3	104.1	40.0
Lean solvent cooler	-2087.1	77.57	40.0
Compressor intercoolers	-913.9	136.4	30.0
Oil cooler	10% of shaft power	70.0	65.0

The heat pump performance depends strongly on the temperature lift it needs to overcome. Higher waste heat temperatures will favor the heat pump performance. This coefficient of performance (COP) is calculated based on source and sink temperatures T_{source} and T_{sink} respectively and the assumption that the practical efficiency of a heat pump is 50% of the ideal heat pump COP (COP_{carnot}).

$$\mathrm{COP}_{carnot} = \frac{T_{sink}}{T_{sink} - T_{source}} \tag{1}$$

$$\mathrm{COP} = 50\% \cdot \mathrm{COP}_{carnot} = \frac{\dot{Q}_{sink}}{P_{shaft}} \tag{2}$$

The goal of 60% final energy reduction translates in a minimum COP of 2.5. The target is to find a combination of waste heat sources that will fulfil the required duty with the highest source temperature and therewith the best efficiency. The amount of heat extracted from a sensible waste heat source is given by:

$$\dot{Q}_{source} = \dot{m}C_p\left(T_{source,in} - T_{source,utilized}\right) \quad (3)$$

where:

$$T_{source,utilized} = T_{evap} + \Delta T_{hex} \quad (4)$$

The limit for Tsource,utilized is the minimum temperature of the waste heat source, Tevap is the evaporation temperature inside the heat pump and ΔThex is the approach temperature which is based on the heat transfer mechanism involved. The mCp term is the mass flow multiplied by the heat capacity and is assumed as constant. For combined sensible and latent heat sources, a function or lookup table needs to be provided that relates available duty to Tsource,utilized:

$$\dot{Q}_{source} = f\left(T_{source,in}, T_{source,utilized}\right) \quad (5)$$

An overview of all approach temperatures used in the calculations is given in Table 2.

Table 2: Approach temperatures and phase transitions

#	Approach temperature ΔT_{hex} [°C]	Phase transition	Phase
Reboiler	5.0	Yes	Liquid to gas
Condenser	15.0	Yes	Gas to partial liquid
Lean solvent Cooler	10.0	No	Liquid
Compressor intercoolers	15.0	Partially	Gas, supercritical or liquid
Heat pump oil cooler	10.0	No	Liquid

In total, six heat integration concepts were evaluated. These concepts differ with respect to the number of compressors in the heat pump and the configuration thereof and the waste heat sources used. Table 3 gives an overview of the different concepts .

Table 3: Overview of the heat integration concepts

#	Concept	Description
A	Basic integration	Only the waste heat sources from the CO_2 capture plant itself
B	Two compressors in parallel	2 evaporation temperature levels with 2 compressors operating side by side as a primary and secondary unit
C	Two compressors in series	2 evaporation temperature levels with 2 compressors operating in series where the output of the bottom compressor is added to the input of the top compressor
D	Compression train intercoolers	The compression train intercooler as an additional waste heat source
E	Two compressors in parallel combined with compression train intercoolers	Concept B combined with concept D
F	Two compressors in series combined with compression train intercoolers	Concept C combined with concept D

These six scenarios have been modelled, using Engineering Equation Solver (EES) [3], and calculated which are presented in the next section.

3. Results and Discussion

Figure 2 depicts the COP results for the different heat integration concepts. Most concepts achieve the threshold of a COP of 2.5, with concepts E & F giving the highest performance. These two concepts have been studied in more detail by thermodynamic cycle calculations in EES. Several natural working media (isobutane, butane, isopentane, pentane) were evaluated for this application. Water (R718) was not considered, due to the very low pressure at the evaporator. The evaluation resulted in isopentane (R601a) as the best choice. Isopentane is a good trade-off between design pressure, isentropic efficiency or capability to reach the required COP of 2.5 and equipment size; the latter is based on the compressor suction volume flow rate.

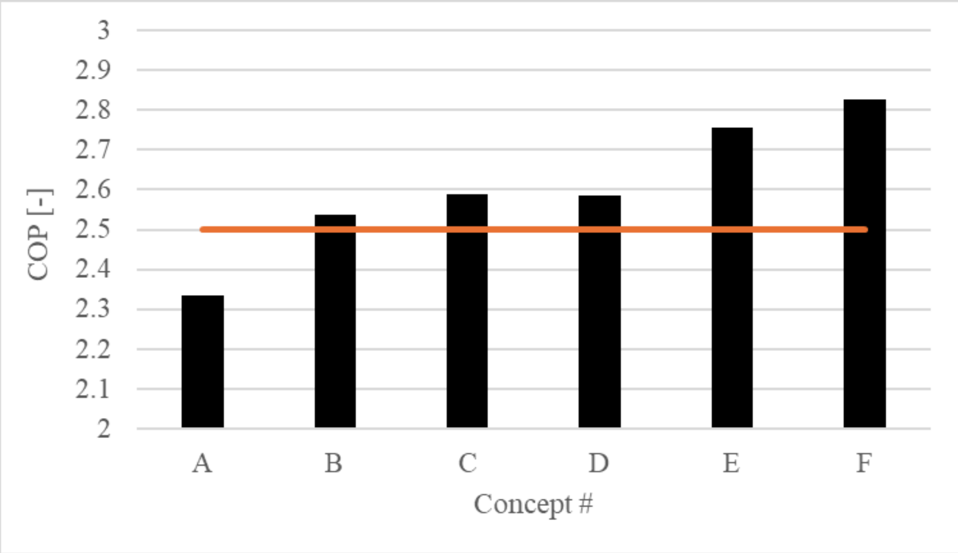

Figure 2 Overall COP for each concept with the red line indicating the threshold COP of 2.50

Detailed analysis also showed that concept F is practically unfeasible due to an unrealistically high compressor efficiency required. Therefore, concept E was selected as final solution. The basic scheme of this heat pump is presented in Figure 3. There are two evaporators, operating at different temperature levels, each connected to a separate compressor, while the condensing temperatures for both cycles are identical. Table 4 shows the operating temperature for each compressor as well as the mass flow isopentane through each compressor. Table 5 provides the duties of the different waste heat sources used by the two compressors, as well as the shaft power and the contribution to the sink.

Table 4 Evaporation & condensing temperature and flow per compressor

Compressor	T_{evap} (°C)	T_{cond} (°C)	Isopentane flow (kg/s)
C1	72.3	130	7.7
C2	47.9	130	13.3

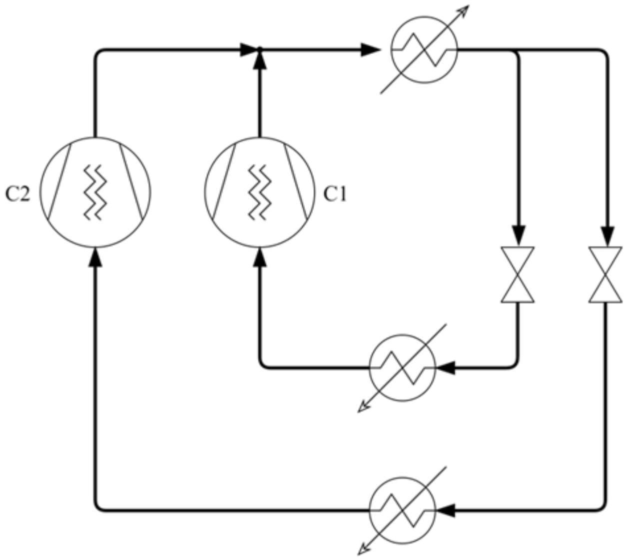

Figure 3 Heat pump layout with 2 compressors operating in parallel

Table 5 Source and sink duties per compressor in the heat pump

Compressor	Condenser (kW)	Cooler (kW)	Oil cooler (kW)	Intercooler (kW)	Shaft Power (kW)	Sink duty (kW)
C1	981.2	0	0	421.7	540.9	1890
C2	580.2	1091	186.9	209.3	1328	3263
Total	1501	1091	186.9	631	1869	5153

4. Conclusions

The integration of a high-temperature heat pump in a CO_2 capture process provides a coefficient of performance of 2.76 and enables more than 60% reduction in final energy input. The optimal configuration employs two parallel compressors and leverages multiple waste heat sources, including compression train intercoolers. This approach is technically feasible, scalable, and offers a pathway for significant decarbonization in energy-intensive industries. Future work should include an economic optimization to find the optimum between capital investment and performance.

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