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Optimal HEN with PHEs for Carbon Dioxide Capture by Amine Absorption Unit at Coal Fired Power Station

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The CO_2 capture processes are of growing interest to scholars in the struggle against global warming, and for the use of CO_2 in the production of clean fuels, chemicals, plastics, and other materials. The post-combustion capture of carbon dioxide from flue gases with monoethanolamine (MEA) Absorption Desorption Unit (ADU) is studied with Process Integration methodology. The optimal structure of the Heat Exchanger Network (HEN) is determined. The study aims to find economically viable options for desorption column parameters by computer modelling and to evaluate the use of novel compact plate heat exchangers (PHEs) with intensified heat transfer. Based on a presented case study, the variation of temperature approach on rich/lean heat exchanger and its influence on heat consumption is discussed. The effect of minimal temperature difference in HEN on the investment cost and its energy efficiency is analyzed. It is shown that the optimal value of minimal temperature difference for HEN with PHEs is 7 °C, which is two times smaller than for HEN based on shell and tube heat exchangers. The use of PHEs in HEN ADU at the same or even smaller purchased cost of heat exchangers saves up to 24 % energy compared to the base case. It is 13 % higher than for the option based on the use of conventional tubular heat exchangers.

1. Introduction

The CO_2 capture processes are of growing interest to scholars not only in the struggle against global warming (Wang et al., 2022), but as a source for producing in the future clean fuels, chemicals, plastics, and other materials (Desport and Selosse, 2022). Today about 200 Mt of carbon dioxide is used to produce urea as fertilizer and other products. Available state-of-the-art reviews show positive developments in carbon dioxide capture and utilization (Shao et al., 2022). But barriers to the deployment of such technologies still remain. The major three are technology readiness, high consumption of energy, and excessive cost (Madejski et al., 2022), The importance of CO_2 sequestration and its different applications has stimulated the interest in CO_2 capture technologies and their economic and market aspects, as pointed out by Centi and Perathoner (2023). All technologies for capturing carbon dioxide can be classified into three categories (Gautam and Mondal, 2023): post-combustion, pre-combustion, and oxy-fuel. The capture of carbon dioxide from flue gases after combustion is the most challenging and energy stringent, as flue gases are at low pressure. It requires special attention to energy efficiency and heat integration (Su et al., 2023). The most common process involves contacting flue gases with a reactive solvent circulating between the absorption column and the stripper column. The process intensification requires studying temperature ranges and sorbents (Akeeb et al., 2022).

The interest in carbon dioxide post-combustion capture increased with the development of new technologies for producing synthetic fuels based on captured CO_2 (Ishaq and Crawford, 2023). It stipulated the development of different CO_2-to-methanol process technologies based on different capture methods (Zhou et al., 2023) and processes of methanol production from natural gas reforming (Ren et al., 2023).

The technology of CO_2 absorption-aided capture from flue gas is not new and has been known for about seventy years. It was used for needs mainly of the food industry in small-scale absorption units. The demands on post-

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combustion CO_2 capture capacities are enormously increasing and require the use of highly efficient and economically feasible technologies. Monoethanolamine (MEA) had been used for CO_2 removal from gas streams since the 1950s due to its high reactivity to CO_2. Now it is still most widespread in post-combustion carbon dioxide capture (Kayahan et al., 2023). These processes are used successfully for carbon dioxide post-combustion capture after firing fossil fuels.

The need for improvement of energy efficiency has stipulated modifications of traditional flow sheets for post-combustion CO_2 capture, depicted in Figure 1. These modifications are overviewed in a paper by Le Moullec et al. (2014). The main aim is to minimize energy consumption by increasing heat recuperation and the proper choice of equipment for absorption and desorption processes. In all these technologies, a similar absorption-desorption unit (ADU) configuration is used. The main component of these structures is a rich/lean recuperative heat exchanger (RLHE) for recuperating the main part of heat energy. The presence of a number of heat sources, heat sinks, and cold and hot streams of different parameters made the scope for the Process Integration methodology described in detail in a book edited by Klemes (2022).

This paper aims to present the perspectives of Process Integration methodology with application of modern intensified heat transfer equipment in the analysis and retrofit of the ADU unit. The possibilities of energy efficiency improvement based on a simple case study and the advantages of Plate Heat Exchangers are shown.

2. HEN ADU analysis with Process Integration methodology

The basic conventional flowsheet of post-combustion carbon dioxide capture with the use of MEA solution as an absorbent is presented in Figure 1. The hot flue gas after combustion is supplied with a flue gas blower (2) to a water scrubber. There it is cleaned and cooled down to the temperature in the absorber (3). In the absorber, the carbon dioxide supplied with flue gas is absorbed by lean MEA solution, and the resulting gas with smaller carbon dioxide content is discharged from the top. The enriched carbon dioxide MEA solution from the bottom of the absorber is supplied by pump (9) to the top of the desorption column (4) through a rich/lean recuperative heat exchanger (RLHE). In RLHE, which is an essential element for all ADU flow sheet modifications, rich MEA solution is heated by a lean MEA solution from the bottom of the desorption column. After that, it is pumped with pump (10) to be cooled down to the required temperature in cooler (8) and supplied to the top of an absorber. The gas-vapour mixture from the top of the desorption column is directed to the condenser (7) and condensed liquid is returned to the desorption column as reflux. The gaseous CO_2 is taken after the condenser for further treatment. The heat for the desorption process is supplied by steam in the reboiler (5), through which the lean MEA solution is circulated to the bottom of the desorption column. The heat consumption of the ADU unit is defined by heat energy supplied to the reboiler. To illustrate the Process Integration approach, the example of ADU stream parameters at a coal power plant is considered, which is analysed in a case study presented in this paper. The concentration of MEA solution is 20%. The stream data are presented in Table 1. In this Table, t_s and t_t are supply and target temperatures, G is the flow rate, C is the specific heat, ΔH is the change of stream enthalpy and "*" denotes the value determined by computer modelling.

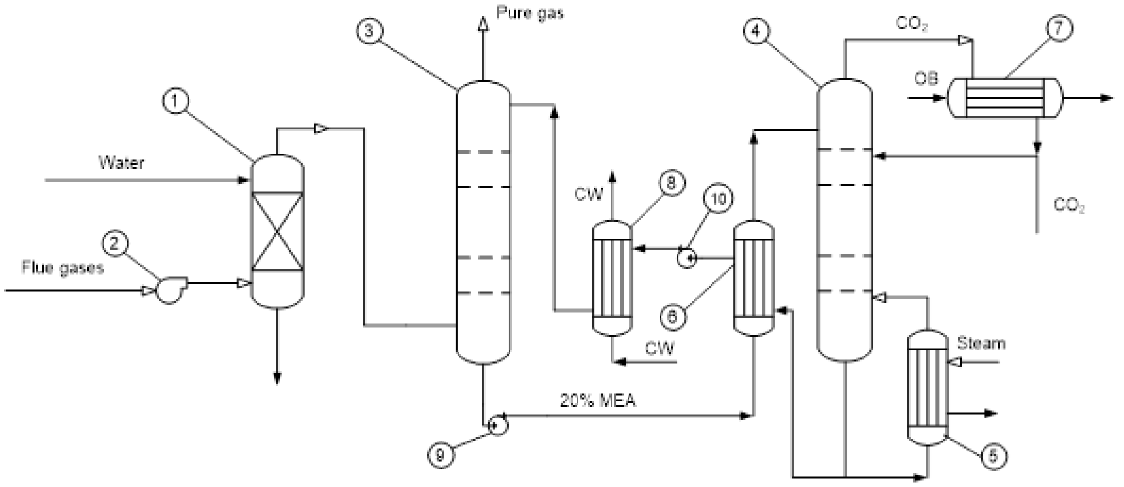

Figure 1: Basic flowsheet of carbon dioxide absorber-desorption capture unit: 1-water scrubber, 2-flue gas blower, 3-absorption column, 4-desorption column, 5-reboiler, 6-rich/lean heat exchanger (RLHE), 7- top condenser, 8-lean absorbent cooler, 9-rich solution pump, 10-lean absorbent pump, CW – cooling water

Table 1: Data of streams

Stream No	Description	Type	t_s, °C	t_t, °C	G, kg/s	C, kJ/kgK	ΔH, kW
1	Flue gas	hot	300.0	40.0	10.84	1.125	3,170
2	MEA after desorber	hot	119.3	40.0	155.0	3.78	46,460
3	Gas-vapour from desorber	hot	111.0	111.0	2.286	-	2,404*
4	MEA to desorber	cold	60.0	100.0	155.0	7.56	23,440
5	Circulation MEA in reboiler	cold	119.3	119.3	-	-	18,986*

Figure 2 presents Composite Curves constructed according to Table 1 data for minimal temperature difference at the Pinch equal to ΔT_{min}= 19.62 °C. The Hot Pinch temperature is 119.62 °C and the Cold Pinch temperature is 99.72 °C. The minimal hot utility requirement is 17,034 kW, and the required cold utility is 23,440 kW. Without the use of flue gas heat all heat in the reboiler is supplied from steam and the hot utility should be 18,986 kW. With the use of flue gas heat, the saved energy is 1,951.2 kW or 10.3 %. The further increase of heat recuperation seems not practical, as Pinch can be switched to the area with a Cold Pinch temperature in the reboiler equal to 119.3 °C, and a Hot Pinch temperature equal to the corresponding temperature of the flue gas. Even at ΔT_{min}= 1 °C in this area, the increase of saved energy will rich an additional 1.31 % only through an enormous heat transfer area. Therefore, increasing the energy efficiency of the ADU with the considered flowsheet is not possible without additional equipment, like heat pumps, and vapour compressors. Another option is to change the process equipment parameters. This paper considers the influence of the temperature of the rich solution feed to the desorption column t_{RD} on the energy efficiency of the whole process.

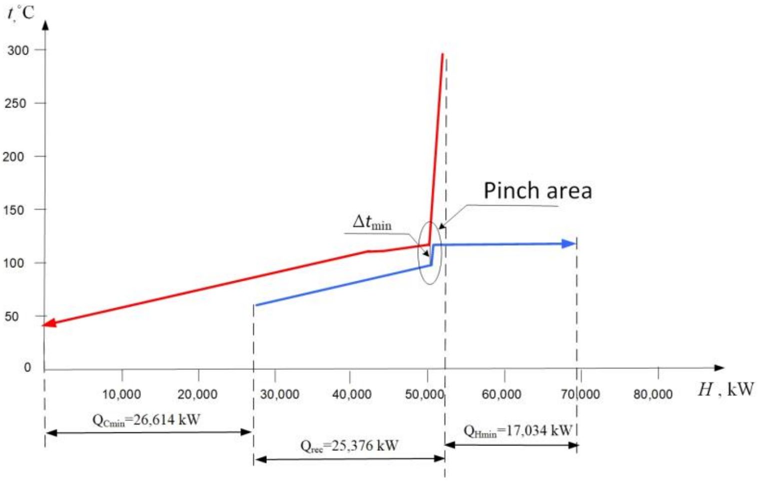

Figure 2: Composite Curves for process in HEN ADU for t_{RD}=100 °C and Δt_{min} = 19.62 °C

The resulting grid diagram of HEN constructed according to the Pinch location shown in Figure 2 is presented in Figure 3. As flue gas is not recommended to cool below 140 °C, the remaining heat is discharged to the direct mixing water cooler. There is also an inevitable small Pinch crossing for heating the rich MEA solution 0.3 °C above the Cold Pinch temperature, so installing an additional HE for such small duty is not economically viable. The form of the Composite Curves led to the conclusion that the location of the Pinch is approximately fixed and the Hot Pinch temperature is equal to the temperature of the lean MEA solution coming from the absorber. The Hot Pinch temperature is very close to the temperature of the rich solution coming to the desorption column. The resulting Minimal Temperature Difference Δt_{min} is closely correlated with the temperature approach at the hot end of the RLHE. For the same temperature in the reboiler, it depends on the temperature of the rich MEA solution feed to the desorption column t_{RD}. Therefore, the analysis can be made with the fixed HEN structure considering the influence of t_{RD} on the capital cost of the required heat exchangers, desorption column process parameters, and the cost of the consumed energy in the reboiler. It is illustrated in the following case study.

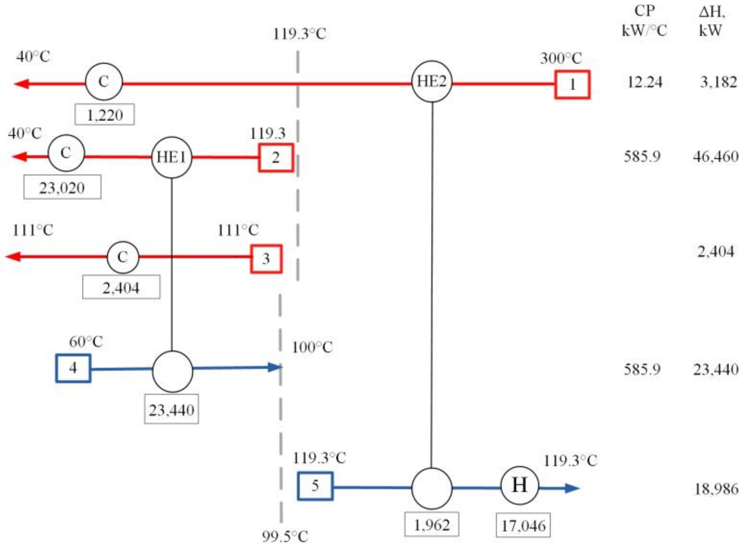

Figure 3: Grid Diagram for HEN of ADU

3. Case study

For the simulation, the post-combustion capture unit of a coal-fired plant with a capacity of 370 t/d CO_2 is selected. As the absorbent, the 20 wt. % MEA solution is considered. The standard flowsheet is analysed (see Figure 1). Initial parameters are those used for Pinch Analysis in the previous section, presented in Table 1.

To determine the performance of the desorption column a model is developed with the use of UNISIM Design software (Honeywell, 2023). To maintain the same flow rate of CO_2 discharged from the system, the reflux ratio of the desorption column was adjusted, keeping the mass fraction of discharged CO_2 in the mixture with steam equal to 0.96. The modelled column has 20 stages. The results of the modelling for different temperatures of rich solution at the hot end of the RLHE heat exchanger (t_{RD}) are presented in Table 2. With an increase in this temperature, the heat duty of the reboiler is decreased, but the rate of this decrease becomes smaller as t_{RD} approaches to the temperature in the reboiler equal to t_{LD}. This is explained by the temperature rise at the top of the desorption column, which is leading to increased steam content in the gaseous mixture going to a condenser. It is required to increase the reflux ratio to maintain the same content of water vapour in carbon dioxide steam that exits the condenser.

The difference between temperatures in the reboiler and the rich MEA solution feed is equal to the temperature approach at the hot end of the RLHE, i.e., $Dt_{RH} = t_{LD} - t_{RD}$. This temperature difference determines the Mean Logarithmic Temperature Difference in the RLHE and with a decrease of Dt_{RH} the heat transfer area of the RLHE is significantly increased. As the heat load of the condenser also increases, it leads also to an increase in the condenser surface area. At the same time, the heat load of a cooler and its heat transfer area decrease.

Table 2: The heat duties at ADU depending on temperatures of incoming to desorber rich solution

t_{RD}, °C	Dt_{RH}, °C	Reflux ratio	Reboiler heat load, kW	Condenser Heat load	Cooling Q_{CL}, kW
85	34.3	0.25	26,980	655.2	35,200
90	29.3	0.33	23,960	860.2	32,000
95	24.3	0.44	21,020	1,160	28,800
100	19.3	0.95	18,986	2,404	25,450
105	14.3	1.7	16,934	3,740	22,090
110	9.3	2.0	15,000	5,004	18,730
112.3	7.0	2.39	14,400	5,940	17,380
115	4.3	3.0	14,156	7,600	15,490
117	2.3	5.2	13,994	10,100	12,820

To estimate the influence of the RLHE temperature approach on the economic efficiency of the ADU, the heat transfer areas of heat exchangers constituting the ADU HEN were calculated. The shell and tube heat exchangers' surface areas with carbon steel tubes and shells were calculated using Aspen Hetran 2006.5 software. The estimated purchased price of heat exchangers was corrected for the year 2021 using the Chemical Engineering Plant Cost Index (CEPCI) as is published by the Chemical Engineering journal (Economic

Indicators, 2022). For 2006 it holds that CEPCI=499.6 and for 2021 that CEPCI=825.7. For comparison on positions of the RLHE and the lean MEA solution cooler, the plate-and-frame heat exchangers of Alfa Laval with stainless steel AISI 304 plates of 0.5 mm wall thickness are considered. The corresponding modelling approach was developed according to the method described by Arsenyeva et al. (2011). The calculations were made for plates of series M, and most of the results were for plates of M15 type (see Alfa Laval, 2023) with an FM frame for a working pressure of 10 bar. The comparison with Alfa Laval quotations for some exchangers gave a discrepancy in a surface area of not more than 10 %.

A more detailed comparison of different available options is made with an estimation of their cost efficiency by analysis of the total annual cost TAC, which can be determined as a sum of annualized capital cost ACC and operating cost OPC. The annualized capital cost is calculated as per Smith (2005) for the comparison of competing projects. The amount of hot utility consumption is determined by the reboilers duty. The cold utility is consumed in a condenser and lean MEA solution cooler. The price of hot utility is taken 440 USD/kW-y and for cold utility 44 USD/kW-y. The calculated costs are shown in the graph of Figure 4.

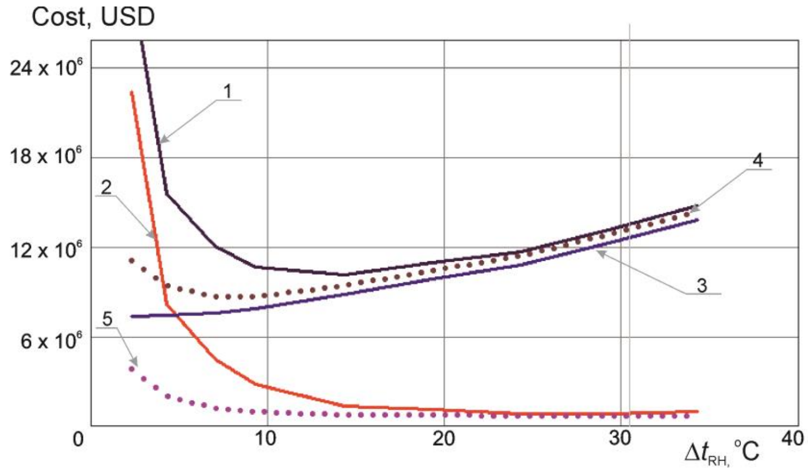

Figure 4: S Annualised costs for HEN ADU: 1- TAC for HEN with shell and tube HEs; 2- ACC for HEN with shell and tube HEs; 3- operating cost OPC; 4- TAC for HEN with PHEs; 5- ACC for HEN PHEs

The variation of the total annualised cost (see Figure 4) shows that its minimal value for HEN with shell and tube heat exchangers and for HEN with PHEs are significantly different and are corresponding to different values of the temperature approaches Dt_{RHmin}. For HEN with shell and tube HE this temperature approach is equal to about 14.2 °C and the corresponding temperature of the rich MEA solution feed to the desorption column is 104 °C. The annualised total cost of the HEN for this option is equal to 10,100,000 USD/y and the purchased cost of HEs in prices of 2021 are estimated as 623,100 USD. From the data presented in Table 2 it follows that the economic saving of hot utility (steam) compared to the base case is 2,052 kW, which is about 11 %.

For HEN with PHEs the temperature approach Dt_{RHmin} is equal to about 7 °C and the corresponding temperature of the rich MEA solution feed to the desorption column is 112.3 °C. The annualised total cost for this option is equal to 8,670,000 USD/y, which is 14.3 % less than for the HEN with shell and tube HEs. The purchased cost of PHEs in 2021 prices is estimated as 544,800 USD or 12.6 % less than for HEN with all shell and tube HEs. The economic saving of hot utility (steam) compared to the base case (Figure 3) is 4,580 kW, which is about 24 % higher than with shell and tube HEs.

4. Conclusions

The methodology of Process integration is a powerful tool for the estimation of the energy targets and the structure of HEN in the process of post-combustion carbon dioxide capture at coal-fired power plants. Its effectiveness is significantly enhanced by the use of modern plate heat exchangers with intensified heat transfer. With the use of computer simulation, it enables significant increase in energy efficiency and the identification of economically viable solutions. The considered case study for basic ADU flow sheets has shown the advantages of the proposed approach for HEN modernisation. With economically efficient use of PHEs, it is possible to decrease energy consumption in the carbon dioxide post-combustion capture unit by up to 24 %, compared to 11 % with traditional shell and tube heat exchangers. It can be achieved with the reduction of investment costs by 10 - 15 %. Further increase of ADU energy efficiency is possible with the application of additional equipment, like heat pumps and vapour compression. Such modifications require further research. The Process Integration methodology with the use of modern PHEs can be recommended for the integration of HEN ADU with the processes at power generation stations and clean fuel production systems from captured carbon dioxide.

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