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Proceeding Paper

Modeling and Simulation of Chemical Absorption Methods for CO_2 Separation from Cement Plant Flue Gases †

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Abstract: Climate change, especially global warming, is observed due to greenhouse gases released on an industrial scale. For this reason, progress is being made around the world to reduce CO_2 emissions and transition to sustainable energy sources. One of the most mature methods of capturing CO_2 from flue gases in industrial sectors is chemical absorption. This work analyzed the absorption process involved in capturing CO_2 from the flue gases of a 1 Mt cement plant. The Aspen Plus modeling package was used to simulate the flue gas pre-treatment; absorption column; and regeneration unit. As a result of the modeling, the optimal values of column sizes; heat duty; and solvent make-up that require the least capital and operational costs for capturing CO_2 in the flue gases of this plant were determined. When a 40% MEA solution was used, and the CO_2 loading in the absorption-stripping process was 0.25 mol/mol, the reboiler heat duty was 4.06 MJ/kg CO_2.

Keywords: climate change; absorption; modeling; heat duty; flue gas; CO_2 capture

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1. Introduction

Since the onset of the industrial revolution, human activities have had detrimental effects on the natural environment, resulting in widespread climatic alterations around the globe. The release of carbon dioxide (CO_2) gas into the atmosphere stands as one of the main contributors causing climate change [1]. Carbon capture, utilization, and storage (CCUS) technology including post, pre, and oxy-fuel combustion CO_2 capture methods has emerged as a very effective method for mitigating anthropogenic carbon dioxide (CO_2) emissions [2].

Currently, the amine-based chemical absorption method has achieved the highest level of maturity in post-combustion CO_2 capture [3]. Amine-based carbon capture technology has been effectively used for capturing CO_2 from flue gases with a low CO_2 concentration [4]. This technology has found application in large-scale power plants, cement plants, and other sectors with significant carbon emissions [5]. Figure 1 illustrates the basic flow diagram of the absorption-based carbon capture process. In this process, the CO_2 present in the flue gas stream, which comes from the cement plant, has a reaction with the solvent inside the absorption column. Subsequently, the solvent, which is enriched with CO_2, is thermally regenerated within the stripper column. The lean-loading solution, which is free from CO_2, is returned to the absorption column after a process of heat exchange with the rich-lean solution and subsequent cooling. The CO_2 stream with a high level of purity is conveyed in a process involving the compression and subsequent usage or storage of the carbon. A flue gas stream that has undergone treatment is discharged into the atmosphere.

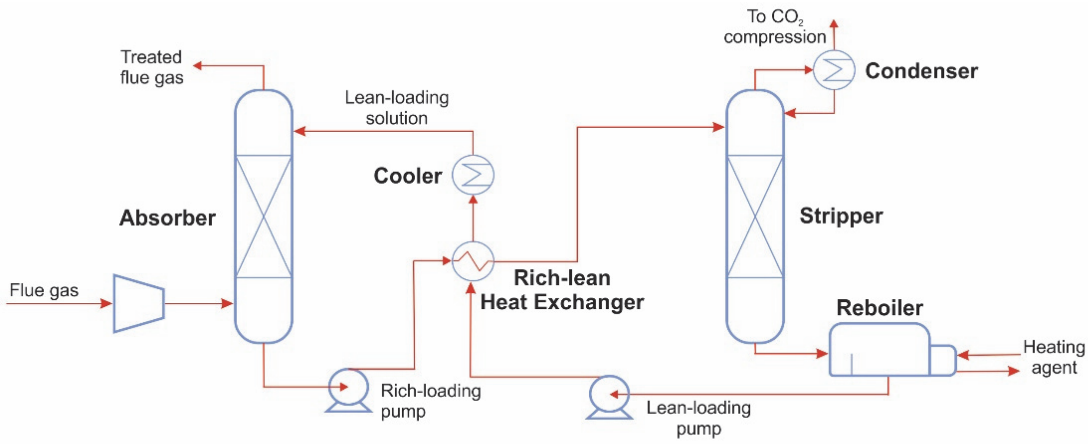

Figure 1. Flow diagram of a basic chemical absorption for CO_2 capture (Modified from [6]).

In this work, a modeling-based study of the "tail-end" chemical absorption method for CO_2 separation from cement plant (with a 1 Mt production capacity annually) flue gases and the determination of the best values in different configuration system cases are considered. This study is considered part of the "Techno-economic evaluation of post-combustion CO_2 capture technologies for cement plant flue gases". Further future work will include comparative studies of this work as a benchmark technology with other near or early-stage post-combustion CO_2 capture technologies.

2. Methodology

2.1. Model Development

The core methodology for this research involves modeling and simulation using the Aspen Plus V12 software. Our key targets and constraints are set as follows: CO_2 removal efficiency must be greater than 90%, CO_2 purity should be greater than 95%, and the occurrence of flooding in the absorption/stripper columns must remain below 75%. The Aspen Plus process simulation software was chosen as the primary tool for modeling and simulating the selected CO_2 capture methods [7]. We developed simulation models that accurately represented the chosen chemical absorption methods. First, the absorber/stripper system was modeled and simulated on the open loop principle. Targets accepted CO_2 removal in the flue gases, the purity of CO_2, and the column packing flooding factor to build the model. Packed column sizing was calculated for the selected packing material [8]. The rate-based model was the most used approach based on the two-film theory in the case of amine-based absorption. In the process of modeling, the following causes should be considered:

(a) Due to the high mole fraction of CO_2, a higher liquid/gas ratio is required for CO_2 molecules to absorb into the liquid phase. This causes more energy to be spent on solvent regeneration;

(b) In order to reduce the column dimension, as well as to increase the gas/liquid transfer surface area, the selection of the packing material and the consideration of pressure drop and flooding are the most important requirements.

2.2. Case Study Scenarios

Our research incorporated case studies to evaluate the performance of the selected chemical absorption methods under diverse operating conditions. These scenarios encompassed variations in solvent properties (30 and 40% wt.) and CO_2 loading (0.134, 0.18, and 0.25 mol/mol) conditions (see Table 1). The composition of CO_2 in the incoming flue gas was consistent across all three cases, with a mole fraction of 0.1891. Examining these scenarios, we estimated acceptable reboiler duty in the stripper column and solvent make-up values in the absorption method of CO_2 capture in cement plant flue gas.

Table 1. Hydraulic design and packing internals for absorption/stripping columns.

	Case 1	Case 2	Case 3
		Absorption column	
Packing diameter	8.6	10	8.8
Packing height	35	45	35
Packing type	RASCHIGPAK 250Y	IMTP	MELLAPAK 350Y
Flooding, %	69	72	78.74
		Stripping column	
Packing diameter	7.6	8.2	5
Packing height	25	30	20
Packing type	PALL	BERL	MELLAPAK 128X
Flooding, %	58	60	72

3. Results and Discussion

Table 2 presents the results of the modeling and simulation of the process of CO_2 separation in cement plant flue gases based on amine absorption. Each case provides information on the composition and the mass flows of various components, including MEA, H_2O, CO_2, N_2, and O_2. All the results fully satisfy the set targets and constraints.

Table 2. Modeling and simulation results.

	Case 1		Case 2		Case 3	
	Treated Flue Gas	**CO_2 Pipe**	**Treated Flue Gas**	**CO_2 Pipe**	**Treated Flue Gas**	**CO_2 Pipe**
			Mole Fractions (%)			
MEA	0.047	0	0.05	0	0.04	0
H_2O	31.407	3.149	30.5	3.16	30.51	3.149
CO_2	1.603	96.731	1.758	96.7	1.76	96.68
N_2	58.078	0.094	58.732	0.11	58.73	0.14
O_2	8.865	0.027	8.96	0.03	8.96	0.03
			Mass Flows (kg/h)			
MEA	409.63	0	413.021	0	364.0955	0
H_2O	80,129.93	1287.60	81,234	1291.54	76,976.9	1278.431
CO_2	9991.938	96,629.89	10,426.2	96,321.52	10,843.8	95,786.71
N_2	230,414.5	59.561	230,401	68.261	230,385.4	88.64532
O_2	40,174.43	19.583	401,168	27.2863	40,165.02	28.98953

The reboiler heat duty represents the amount of heat energy required to regenerate the MEA absorbent and release the captured CO_2. This value in Case 1 is 5.62 MJ per kg of the captured CO_2. In Case 2, the reboiler heat duty is slightly lower at 4.72 MJ/kg CO_2. This indicates that Case 2 requires less energy to achieve the same level of CO_2 capture compared to Case 1. Case 3 has the lowest reboiler heat duty of 4.06 MJ per kg CO_2. This suggests that it is the most energy-efficient among the three cases for capturing CO_2 using MEA absorption (see Figure 2).

In terms of MEA and water make up, Case 3 requires the lowest MEA and water makeup rate, which are 364 kg/s and 61.9 t/h, respectively. This implies that it consumes less MEA and H_2O to achieve CO_2 capture compared to the other cases with a smaller column dimension.

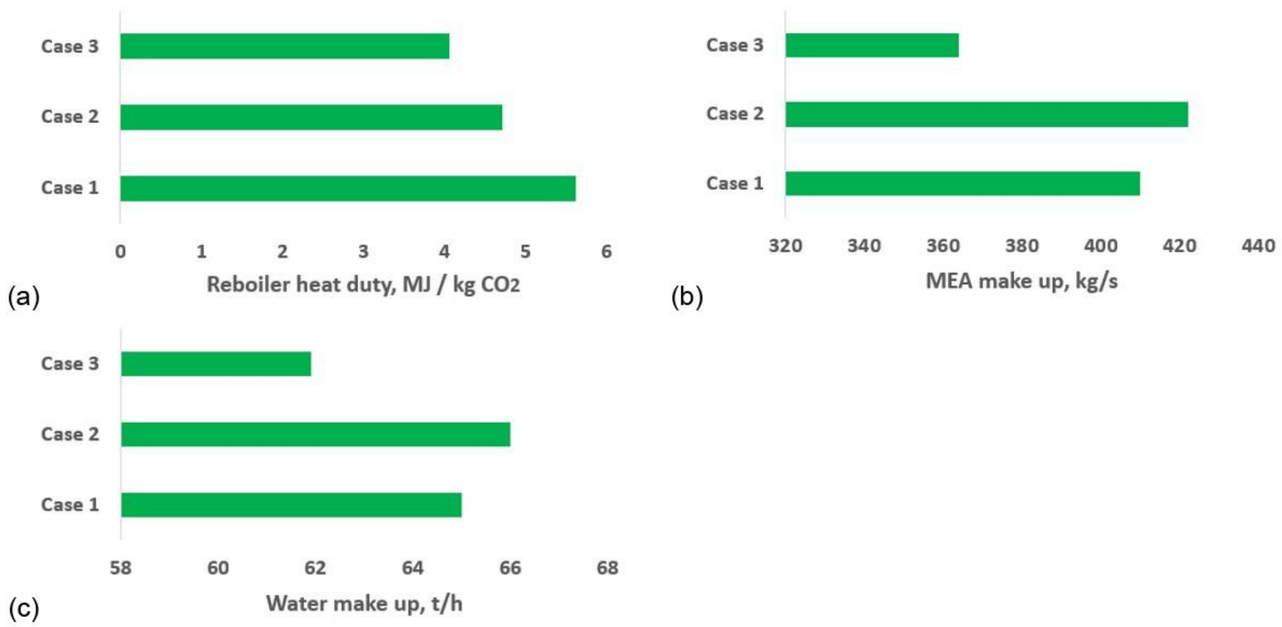

Figure 2. Case study scenarios results: (**a**) reboiler heat duty; (**b**) MEA make up; (**c**) water make up.

4. Conclusions

This study analyzed the CO_2 capture process in a 1 Mt cement plant using the Aspen Plus modeling software. The column sizes, heat duty, and liquid make-up values were determined using the modeling and case study methodology to minimize capital and operational costs. The reboiler heat duty with 4.06 MJ/kg of CO_2 in the stripper column was found to be the most energy-efficient among the three cases, with MEA 40% wt. and 0.25 mol/mol CO_2 loading condition, which requires the lowest MEA and water makeup rate, compared to other cases with smaller column dimensions.

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Abbreviations

CCUS	Carbon capture, utilization, and storage
CO_2	Carbon dioxide
MEA	Monoethanolamine
H_2O	Water
N_2	Nitrogen
O_2	Oxygen

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