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Energy Procedia 1 (2009) 4315–4321
Energy Procedia
www.elsevier.com/locate/procedia

GHGT-9

Integration of CO_2 capture unit using blended MEA-AMP solution into coal-fired power plants

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Abstract

This study evaluated feasibility of using blended MEA and 2-amino-2-methyl-1-propanol (AMP) in the CO2 capture unit that is integrated into a supercritical coal-fired power plant. The evaluation was carried out by using the integrated power plant and gas absorption model developed at the University of Regina, Canada. Simulation results were presented in terms of energy requirement for solvent regeneration, sizes of absorber and regenerator, cost of CO2 capture and energy penalty. Conventional MEA process was also simulated and used as a benchmark for a comparison purpose.

Keywords: CO_2 capture; coal-fired power plant; process integration; net efficiency

1. Introduction

Capturing carbon dioxide (CO_2) generated from coal-fired power plants is an important strategy that helps mitigate greenhouse gas emissions from power utility sector. One of the challenges in the field of CO_2 capture is to select or develop energy-efficient and cost-effective capture technology that can be integrated into the power plants with a minimum impact on the electricity generation capacity. By far, amine-based absorption is the most suitable technology for capturing CO_2 from low-pressure flue gas. However, the cost associated in this process is prohibitively high, mainly due to excessive energy consumption during amine regeneration. To make the amine-based process more attractive, the energy required by the process must be reduced without sacrificing CO_2 capture performance. This may be achieved by using monoethanolamine (MEA)-based blends as an alternative solvent to the conventional MEA. Our study focuses on a feasibility evaluation of using blended MEA and 2-amino-2-methyl-1-propanol (AMP) in the CO_2 capture unit that is integrated into a supercritical coal-fired power plant. The evaluation provides the information on energy consumption, size of major process equipment as well as cost of CO_2

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doi:10.1016/j.egypro.2009.02.244

capture. It also provides the information on how the CO_2 capture unit using this alternative blend would have an impact on electricity generation in terms of energy penalty if it is integrated into the power plants.

2. Methodology

An integrated power plant and gas absorption model developed at the University of Regina, Canada was used for process simulation. It consists of two working modules; power-cycle and CO_2 capture. The power-cycle module comprises a series of interconnected sub-models of individual components in the steam power cycle including a coal-fired boiler, an air pre-heater, steam turbines (*i.e.* high pressure, HP; intermediate pressure, IP; and low pressure, LP), a series of open and closed feed water heaters (FWHs), a low pressure condenser, and boiler feed water pumps. The power-cycle module was built on the principles of coal combustion, combustion chemistry, heat transfer from combustion zone to the generated flue gas and steam, and thermodynamics of steam power cycle. The CO_2 capture module, the second component of the integrated model, was developed specifically for evaluating the performance of CO_2 absorption process using single- and blended-amine solutions. The capture module enables the generation of design specifications of the entire absorption process including CO_2 absorber, solvent regenerator (or stripper) and heat-exchangers, as well as the operational information of the process such as reboiler heat-duty and consumption of other process utilities (electricity and cooling water). In addition, the capture module also enables the evaluation of the overall cost of CO_2 capture as it consists of an economic sub-module that was built to estimate all capital and operating economic features including direct capital, indirect capital, working capital, operating labor, utility cost, maintenance and repair expenditure, fixed charges, depreciation, plant overhead cost, and administrative cost. Details of the integrated model and the input required can be found in our previous work [1].

3. Simulation Basis

The simulated coal-fired power plant was the supercritical-type which combusts lignite coal from North Dakota and produces a fixed 8,000 tonnes CO_2 per day. It was configured to have 8 feed water heaters and generate a main steam at 28.5 MPa/ 600^oC, a reheated steam at 6.0 MPa/ 600^oC, and a low-pressure turbine backpressure of 5 kPa. The power plant was connected to an amine-based CO_2 capture unit for post-combustion treatment. The CO_2 capture unit is the conventional type with a 90% removal target. Its absorber and regenerator are packed with 2-in Pall rings. A number of amine solutions were used in simulation, including single-MEA and MEA-AMP blend with three different mixing ratios, 2:1, 1:1, and 1:2 mol/mol. MEA was used as a benchmark for comparison purposes.

4. Results and Discussion

4.1 Performance of MEA Process

In this study, the performance of CO_2 capture unit was evaluated in two terms; 1) energy requirement for solvent regeneration (reboiler heat-duty) and 2) size of process equipment particularly absorber and regenerator. These two were chosen as the performance indicator because they reflect inter-relationship between operations of absorber and regenerator and cost associated [2]. Figure 1 shows a typical behavior of reboiler heat-duty of MEA process as a function of CO_2 loading of lean amine (lean loading) at two different regeneration temperatures *i.e.* 103 and 110^oC. It is apparent that the reboiler heat-duty of MEA decreases with lean loading. The heat-duty however increases after the lean loading exceeds the critical value where the heat-duty reaches the minimum value.

Figure 1 also shows that operating the regenerator at a higher temperature (with a slight increase in regeneration pressure) and/ or at a higher lean loading (below a minimum lean loading) presents an opportunity for a reduction in the reboiler heat-duty. At 103^oC, the reboiler heat-duty could reach as high as 100,767 BTU/lbmol CO_2 when a regenerator is operated to achieve a lean loading of 0.20 mol/mol. The heat-duty could be reduced to a minimum of 62,000 – 64,000 BTU/lbmole CO_2 when a higher lean loading of 0.28 – 0.38 mol/mol is the regeneration target. A lower range of heat-duty is required at the regeneration temperature of 110^oC. That is, the heat-duty of 88,000 BTU/lbmole CO_2 is required for regenerating MEA solution down to 0.17 mol/mol lean loading. The minimum heat-duty of 56,000 BTU/lbmole CO_2 can be achieved when the lean loading increases to 0.28 mol/mol.

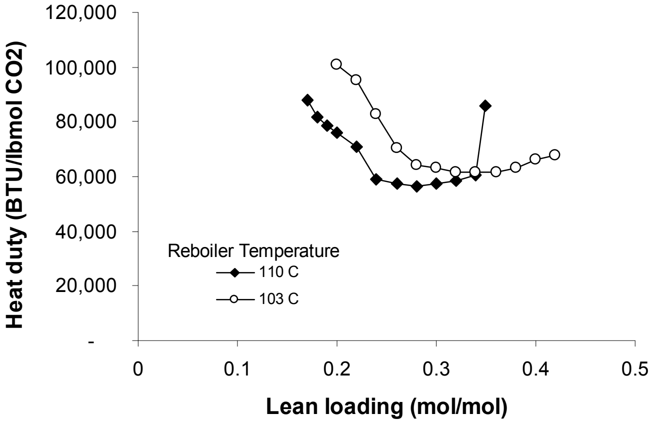


Figure 1 Reboiler heat-duty of MEA system.

Figure 2 shows relative sizes of absorber and regenerator as a function of lean loading. Increasing the lean loading reduces the size of regenerator, but increases the size of absorber due to a lower CO_2 capture performance in the absorber to achieve a given capture target (90% capture efficiency in this case).

By combining the above effects of lean loading on both energy requirement and size of process equipment, an overall cost of CO_2 capture was evaluated and presented in Figure 3. It is shown that regenerating the MEA solution down to a very low lean loading of 0.2 mol/mol although favors mass-transfer performance of the absorber, but it consumes an excessive amount of energy for solvent regeneration, thus driving the capture cost to as high as US$ 40/ton CO_2 captured. The slight regeneration with lean loading of 0.42 mol/mol also offers an unattractively high cost of capture (US$ 40/ton CO_2) as it requires a sizable absorber for CO_2 capture activity as well as a large amount of energy for pumping MEA solution at a very high circulation rate. Operating the MEA process within these two lean-loading extremes can help reduce the capture cost down to a minimum cost of US$25 – US$27 per ton CO_2 captured.

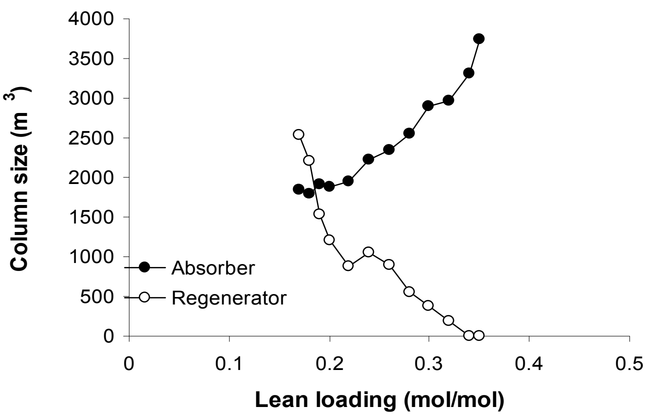


Figure 2 Size of CO_2 absorber and regenerator as a function of CO_2 lean loading (MEA system)

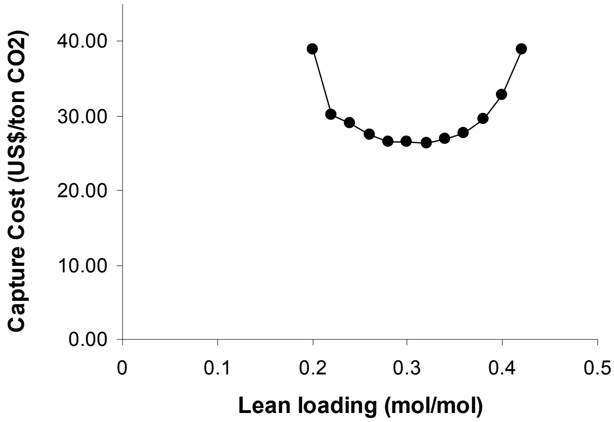
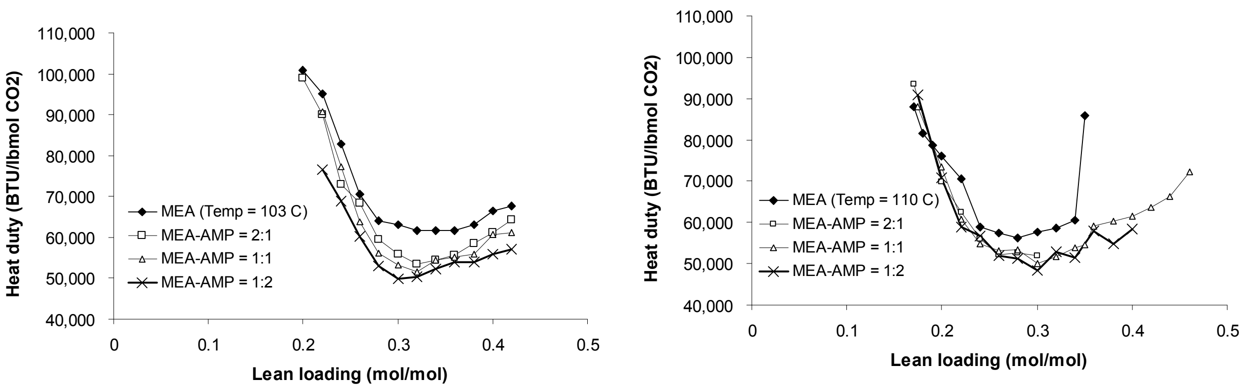


Figure 3 CO_2 capture cost as a function of CO_2 lean loading (MEA system)

4.2 Performance of MEA-AMP Blend Process

MEA-AMP blend is a promising amine that could replace MEA for CO_2 capture due to its energy requirement for solvent regeneration and CO_2 capture performance. According to our previous work [3-4], the MEA-AMP blend requires a lower reboiler heat-duty while offering the CO_2 capture performance only slightly lower than MEA. The information of such reboiler heat-duty and mass-transfer performance was used in our CO_2 capture model to produce the following results.

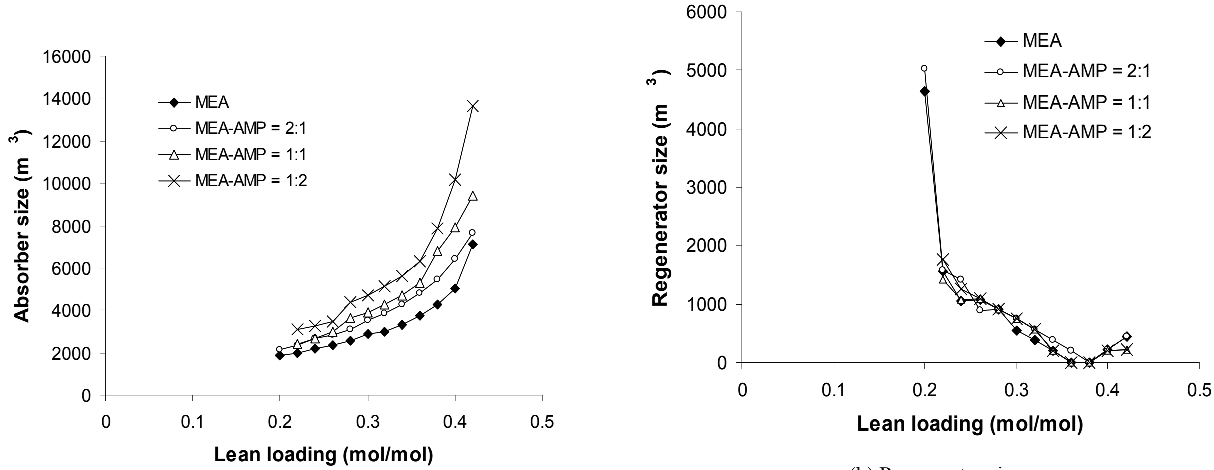
Figure 4 shows that the reboiler heat-duty of MEA-AMP blend behave similarly to that of MEA, *i.e.* the heat-duty can be reduced to the minimum value at the critical lean loading. The MEA-AMP blend offers a minimum heat-duty of 50,000 BTU/lbmol CO_2 which is 11 – 19% lower than the heat-duty of MEA. A reduction in regeneration temperature from 110 to 103°C leads to an increase in reboiler heat-duty of MEA by about 11%. In contrary, decreasing the regeneration temperature in the MEA-AMP process results in a slight impact on the minimum heat-duty. This presents a great opportunity for the MEA-AMP process to use a lower-pressure and lower-temperature steam as the heat source for solvent regeneration compared to the requirement for MEA process, thus reducing energy penalty of the power plant when the CO_2 capture unit is integrated into.



(a) Reboiler temp = 103 °C (b) Reboiler temp = 110 °C

Figure 4 Reboiler heat-duty of MEA-AMP blend system.

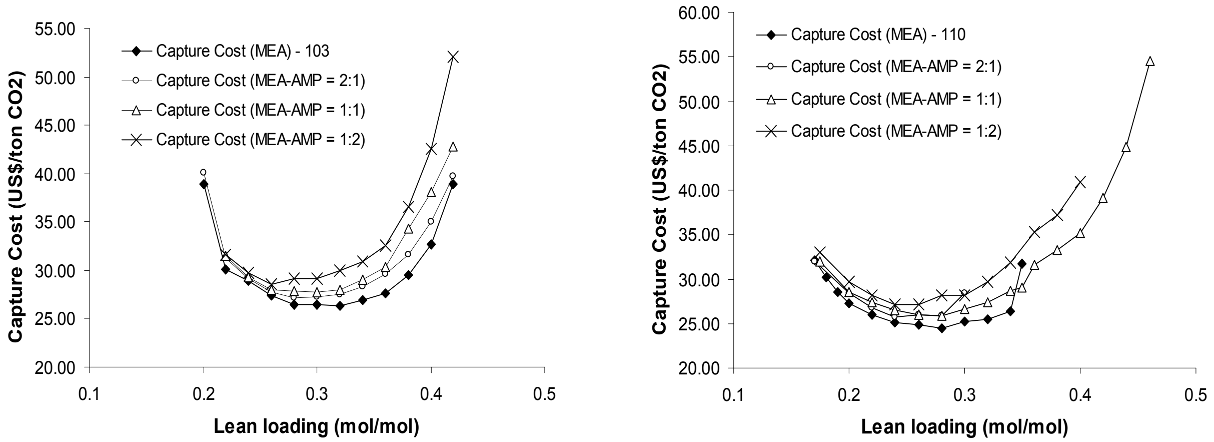
Figure 5 shows that capturing CO_2 using MEA-AMP blend requires a larger absorber compared to that using MEA. The absorber size depends largely on mixing ratio of MEA-AMP. With a mixing ratio of 2:1 (MEA:AMP), the blend requires an absorber with up to 22% taller compared to the MEA. Increasing AMP concentration in the blend results in an even taller absorber. Approximately 47% and 78% increases in absorber height were found for the mixing ratio of 1:1 and 1:2, respectively. Figure 4 also shows that the regenerator size does not change significantly when MEA-AMP blend is used in place of MEA.



(b) Regenerator size

Figure 5 Size of CO_2 absorber and regenerator as a function of CO_2 lean loading (MEA-AMP blend system)

By combining the information of energy requirement and equipment size, cost of CO_2 capture using MEA-AMP blend was evaluated and plotted in Figure 6. Results show that the use of MEA-AMP blend leads to a slight increase in the minimum CO_2 capture cost compared to the cost derived from the use of MEA. The minimum capture cost for MEA ranges from US$ 25 to 27 per ton CO_2 while that for the blend is approximately US$ 27 – 29 per ton CO_2. Although the MEA-AMP blend requires higher CO_2 capture cost, it should be kept in mind that its lower energy requirement for solvent regeneration is beneficial to the power plant as it helps reduce energy penalty.



(a) Reboiler temp = 103 ºC

(b) Reboiler temp = 110 ºC

Figure 6 CO_2 capture cost as a function of CO_2 lean loading (MEA-AMP blend system)

4.3 Integration of CO_2 Capture Unit into Coal-Fired Power Plants

Figure 7 shows net efficiency of supercritical coal-fired power plants with and without CO_2 capture unit. The net efficiency and net power output of the power plant without CO_2 capture unit were estimated to be 46.5% and 480 MW. By using MEA in the CO_2 capture unit, the net efficiency of the integrated power plant could be reduced to as low as 35.9%. Operating the MEA unit with a moderate lean-loading (0.28 – 0.34 mol/mol) helps increase net efficiency of the power plant to 39.4%, leading to the minimum energy penalty of 7.1% point drop. Figure 7 also shows that the use of MEA-AMP blend for CO_2 capture yields a higher net efficiency of the integrated power plant. A net efficiency of 40.3 – 40.7% can be achieved regardless of mixing ratio of MEA-AMP blend. This indicates that replacing MEA with MEA-AMP blend can help reduce the energy penalty of the power plant from 7.1% to 5.8% point drop.

Figure 8 shows distribution of energy utilization and output generated from the power plant equipped with CO_2 capture unit using both conventional MEA and MEA-AMP blend at different mixing ratios. It is apparent that MEA causes the net electricity output to drop from 480 MW to about 407 MW, while MEA-AMP blend causes the net output to reach almost 420 MW.

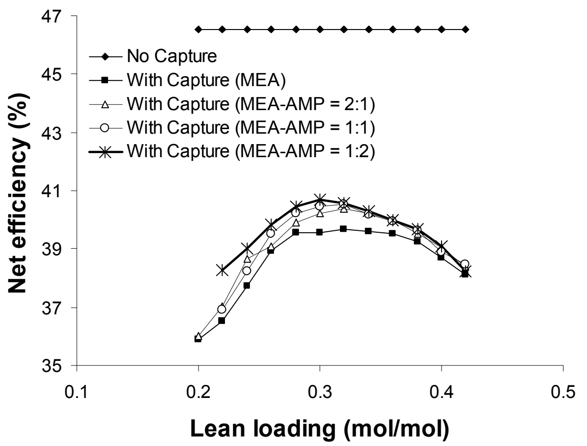


Figure 7 Net efficiency of supercritical coal-fired power plant with and without CO_2 capture

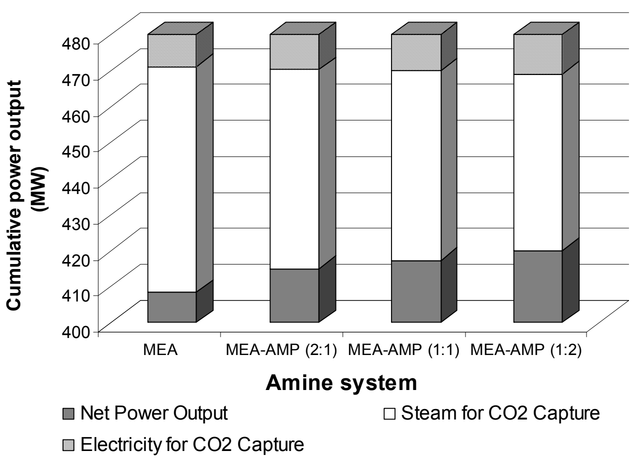


Figure 8 Energy distribution of supercritical coal-fired power plant with CO_2 capture

5. Conclusions

The MEA-AMP blend exhibits a great promise for CO_2 capture in supercritical coal-fired power plants. It requires less energy for solvent regeneration, uses a lower-quality steam and yields less energy penalty compared to MEA. However, cost of CO_2 capture using MEA-AMP blend is slightly higher than MEA due to a larger size of absorber to achieve a given CO_2 removal target.

Acknowledgement

The Natural Sciences and Engineering Research Council of Canada (NSERC) is gratefully acknowledged for generous financial support.

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