Enhancing the energetic efficiency of MDEA/PZ-based CO₂ capture technology for a 650 MW power plant: Process improvement

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HIGHLIGHTS

- MDEA/PZ solutions are more energetically efficient for post-combustion CO₂ capture.
- Various process improvements effectively enhance the process energy efficiency.
- A reboiler heat duty (Qreb) of 2.24 G J/t CO₂ was achieved.
- The net power efficiency penalty was reduced from 9.13% to 7.66%.

ABSTRACT

Post-combustion CO₂ capture (PCC) facilities are set up at the power plants to reduce their carbon footprint. However, the high energy demand of the amine-based PCC technologies significantly decreases the net energy efficiency of a power plant. This work focused on developing an optimal amine-based PCC technology by carefully analyzing and integrating the energy flow. The methyldiethanolamine (MDEA) solution of lower reaction heat with CO₂ is found to be a superior solvent than monoethanolamine (MEA). Process analysis using the equilibrium stage model in Aspen Plus was performed to investigate the effects of piperazine (PZ) promoter and various operation parameters such as absorption pressure, stripping pressure, CO₂ loading in lean solution, and CO₂ removal ratio on the net efficiency penalty of MDEA/PZ-based PCC process. Several enhancement measures, including the absorber intercooling, simple rich-split, advanced rich-split, and stripper interheating, were found significantly improving the process energetic efficiency. A reboiler heat duty (Qreb) as low as 2.24 G J/t CO₂ was achieved which is 27.7% lower than that of its counterpart (MEA). The enhanced MDEA/PZ-based technology leads to a low net power efficiency penalty of 7.66% which is 16.1% less than that of the benchmark MEA-based technology. This improvement corresponds to an absolute increase of 1.47% in net efficiency of a 650 MW power plant with PCC units.

1. Introduction

Anthropogenic CO₂ emissions are believed to be the primary contributing factor toward the increasing global warming [1,2], and they are mainly attributed to the combustion of fossil fuels [3]. In the near future, fossil energy will continue to dominate our energy supply because the application of renewable energies is still far from matching the total energy consumption [4]. Carbon capture and storage (CCS) is a post treatment strategy to reduce CO₂ emissions [5–7]. Thus, increasingly more stationary CO₂ emission sites such as power plants are setting up CO₂ capture facilities. However, the power generation cost was increased by 40–85% after installation of a CO₂ capture unit [8,9]. Thus developing low-cost and energy-saving CO₂ capture technologies is very attractive [10,11].

Alkanolamine solution is the most commonly used solvent for PCC process and is widely applied in industry [10,12,13]. Unlike CO₂ separation in natural gas production and ammonia production, the partial pressure of CO₂ (13 kPa) from a power plant is significantly lower [14,15]; monoethanolamine (MEA) is usually adopted as the absorbent because of its high reactivity with CO₂ [13,16,17].

Fig. 1 shows the pattern of energy consumption for an MEA-based PCC process with 4.2 Mt CO₂/a capture capacity, in which...
Table 3. Distribution of total energy consumption and three components of $Q_{reb}$ in an MEA-based PCC process [13, 18].

<table>
<thead>
<tr>
<th>Component</th>
<th>Energy Consumption (GJ/t CO2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total energy</td>
<td>3.6</td>
</tr>
<tr>
<td>Sensible Heat</td>
<td>0.68</td>
</tr>
<tr>
<td>Reactor Heat</td>
<td>2.12</td>
</tr>
<tr>
<td>Useless Heat</td>
<td>0.37</td>
</tr>
<tr>
<td>Pump work</td>
<td>0.8</td>
</tr>
<tr>
<td>Compression work</td>
<td>0.29</td>
</tr>
<tr>
<td>Reboiler duty</td>
<td>0.4</td>
</tr>
<tr>
<td>Blower work</td>
<td>0.08</td>
</tr>
</tbody>
</table>

$n_{CO_2}$ amount of CO2 desorbed from the rich solution, kmol/h
$L$ circulation rate of the absorbent, kg/h
$c_p$ heat capacity of the rich solution, kJ/(kg·K)
$T_{rich}$ temperature of the rich stream (S1) at the stripper inlet, °C
$T_{lean}$ temperature of the lean stream (S2) at the absorber inlet, °C
$T_{reb}$ temperature of the reboiler (E2), °C
$T_{E1}$ temperature of the stripper condenser (E4), °C
$T_{E2}$ logarithmic mean temperature difference of lean/rich heat exchanger (E1), °C
$P_{strip}$ stripping pressure, MPa
$P_{abs}$ absorption pressure, MPa
$Q_{reb}$ reboiler (E2) heat duty, GJ/t CO2
$\Delta H_{abs} CO_2$ reaction enthalpy of CO2 with amine (MEA or MDEA/PZ blends), kJ/kmol
$\Delta H_{vap} H_2O$ vaporization heat of H2O, kJ/kg
$c_p H_2O$ heat capacity of H2O, kJ/(kg·K)
$n_{H_2O vap}$ Amount of the hot stream entering the condenser (E4), kg/h

$\Delta H_{abs} CO_2$ is much smaller than that of the carbamate formed by MEA and CO2 (95 kJ/mol CO2) [14,23,24–25]. Extensive investigations have been done on the CO2-MDEA-H2O system such as the chemical [26–29] and physical absorption data [30–34] as well as the equilibrium model [35]. However, MDEA itself shows low CO2 absorbing rate which limits its application in CO2 separation processes [36]. Piperazine (PZ) was found to be an absorption rate promoter for MDEA [37]. The MDEA/PZ blends also have a low reaction enthalpy [25], corresponding to only 1.6 GJ/t CO2. And the resultant aqueous MDEA/PZ solution shows both a high CO2 absorption capacity and adequate CO2 absorption rate [25]. The equilibrium constants of the CO2-PZ system was reported [38–40]. The CO2 loading of various aqueous MDEA/PZ solutions was found increasing with the increase of PZ content [41–43]. Bishnoi et al. developed an absorption model for the CO2-MDEA/PZ-H2O system which is capable of predicting the CO2 absorption rate, enhancement factor, the height and volume of the transfer unit well [44]. However these works were limited to the low PZ content.

Generally an MDEA/PZ solution of 45 wt.% MDEA and 5 wt.% PZ was used to remove the CO2 from the feed stream in natural gas.
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