Modelling\simulation and optimization of large-scale post-combustion CO2 capture using a rotating packed bed absorber and packed bed stripper

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Abstract

Rotating packed bed (RPB) is capable of reducing the size, footprint, and cost of the post-combustion carbon capture (PCC) process when used as absorbers and strippers. RPB can be operated with higher monoethanolamine (MEA) concentration (>55 wt%). At these concentrations, there is potential for higher absorption performance and lower energy demand for solvent regeneration. However, previous studies have not investigated the optimal MEA concentrationto operate the RPB absorber and PB stripper for large-scale PCC processes. This study investigates the optimal solvent concentration in MEA-based PCC using an RPBabsorber and packed bed (PB) stripper for 250 MW combined cycle gas turbine (CCGT) power plants. The rate-based model of the RPB absorber was developed in Aspen Custom Modeller® (ACM) V11. The accuracy of the RPB absorber model was verified by validating it with experimental data. The RPB absorber model correctly predicted the experimental data and was then scaled up to deal with flue gas from a 250 MW CCGT power plant. The RPB Absorber model was exported to Aspen Plus® and integrated with PB stripper to develop the closed loop of the large-scale PCC process. This large-scale model was used for process analysis and optimization studies. Optimisation results showed that the lowest total energy consumption of 4.46 GJ/tCO2 was found at an optimal MEA concentration of 75 wt%. Going forward, we will perform an elaborate economic analysis based on the optimized process to determine the optimal MEA concentration that results in the lowest CO2 capture cost.

**Keywords**: Post-combustion carbon capture, chemical absorption, rotating packed bed, Combined cycle gas turbine power plant, optimisation.

* 1. Introduction

Carbon dioxide is a greenhouse gas that is responsible for climate change. Fossil fuel-fired power plants are the largest CO2 emitters. Hence CO2 emissions reduction efforts must be targeted at these plants. The amine-based post-combustion capture (PCC) has a technology readiness level of 9 and has been deployed at a commercial scale to capture CO2 from coal-fired plants at Boundary Dam in Canada and the Petra Nova project in the USA [1]. This makes the technology the most mature among the different carbon capture technologies. The amine-based PCC is mostly operated using packed bed (PB) columns as absorbers and strippers and 30 wt% MEA as a solvent. The bottlenecks of the process include the high energy demand and huge equipment sizes that result in high costs and a high plant footprint. These have prevented the rapid and extensive implementation of the process at a large scale. The rotating packed bed (RPB) technology can reduce the size and the costs of the PCC process when used to replace the PB absorber [2].

The RPB consists of an annular packed bed connected to two-side disks that are mounted on a rotating shaft and housed in a casing. The liquid generally flows radially outward from the inner periphery of the packing due to centrifugal acceleration while the gas enters into the casing and then flows radially inward from the outer periphery of the RPB due to the pressure gradient. The gas and the liquid phases are exposed to enormous centrifugal acceleration which is many times the gravitational acceleration in PBs. This enhances mass transfer in the bed and areas between the packing and the casing. This is the reason for the substantial reduction in packing volume in RPBs compared to PBs. RPB can also be operated with higher MEA concentration as it can break viscous high MEA concentration into tiny liquid films[3]. Higher MEA concentration could reduce solvent flow to the stripper and the regeneration energy demand. However, no study has demonstrated the optimal design and operation of the RPB absorber at different solvent concentrations. Therefore, this study aims to investigate the optimal solvent concentration in MEA-based PCC using an RPB absorber and PB stripper for a 250 MW CCGT power plant.

* 1. Model development for RPB absorber
		1. Mass and energy balance equations

The rate-based model is used to describe the CO2 absorption in RPB. The RPB is discretised radially into smaller packing segments. The mass and heat transfers, chemical reactions and hydrodynamics are considered in each discretised segment. All the equations used to describe the model were implemented and solved in the equation-oriented process simulator Aspen Custom Modeler® (ACM). The equation describing the mass balance in the gas and the liquid phases is given by Eqs. 1 and 2. The energy balance in the gas and liquid phases is described by Eqs. 3 and 4.

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| --- |
| ***Mass balance*** |
| Gas phase | $$0= \frac{1}{2πrZ}\frac{∂\left(F\_{g}y\_{i}\right)}{∂r}-a\_{gl}N\_{i}$$ | 1 |
| Liquid Phase  | $$0=-\frac{1}{2πrZ}\frac{∂\left(F\_{l}x\_{i}\right)}{∂r}+a\_{gl}N\_{i}$$ | 2 |
| ***Energy balance*** |
| Gas Phase  | $$0=\frac{1}{2πrZ}\frac{∂\left(F\_{g}C\_{p,g}T\_{g}\right)}{∂r}-a\_{gl}h\_{gl}\left(T\_{l}-T\_{g}\right)$$ | 3 |
| Liquid phase  | $$0=-\frac{1}{2πrZ}\frac{∂\left(F\_{l}C\_{p,l}T\_{l}\right)}{∂r}+a\_{gl}\left(h\_{gl}\left(T\_{l}-T\_{g}\right)-∆H\_{rxn}N\_{CO2}-∆H\_{vap,H2O}N\_{H\_{2}O}\right)$$ | 4 |

* + 1. Mass transfer, heat transfer and hydrodynamic models

The gas and liquid mass transfer coefficients, gas-liquid interfacial area, liquid holdup, pressure drop and heat transfer coefficient in the RPB absorber model are estimated using correlations in Table 1.

Table 1 Correlations used for mass and heat transfers.

|  |  |
| --- | --- |
| Correlations | Reference |
| Gas-phase mass transfer coefficient | Onda et al. [4] |
| Liquid-phase mass transfer coefficient | Tung and Mah [5] |
| Interfacial area | Billet and Schulte [6] |
| Liquid holdup | Burns et al. [7] |
| Pressure drop | Llerena-Chavez and Larachi [8] |
| Heat transfer coefficient | Chilton and Colburn [9] |

* 1. Results and discussions
		1. Model validation and scale-up

The RPB absorber model was validated with pilot scale data from Jassim et al. [10]. Case 1 with 4 experimental runs was chosen for model validation. The RPB has an inner diameter of 0.156 m, outer diameter of 0.398 m, and axial height of 0.025 m. It is packed with stainless steel small mesh packing. As shown in Figure 1, the RPB absorber model accurately predicted the CO2 capture level compared to the experimental data in Jassim et al [10].

Figure 1: Model predictions vs. experimental data for capture level

Upon validation, the RPB absorber was scaled up using the procedure described by Otitoju et al. [2]. The scale-up involves determining the basic dimensions (inner packing radius, outer packing radius and axial height) of the RPB required to capture CO2 from the flue gas of a 250 MW CCGT power plant.

* + 1. Whole large-scale PCC process simulation

The large-scale RPB absorber model developed in ACM is packaged and exported as a custom modelto Aspen Plus®. The RPB absorber model is integrated with the PB stripper model to develop the model of the whole process. For a detailed description of the stripper model, validation and scale-up, the reader is referred to Otitoju et al.[11].

Table 2: Summary of design specifications and operating conditions

|  |  |  |
| --- | --- | --- |
| Operating conditions | Absorber | Stripper  |
| Type | RPB  | PB |
| Inner diameter (ID) (m) | 3 | - |
| Outer diameter (OD) (m) | 9.72 | 8.2 |
| Height (m) | 1.26 | 20 |
| Packing type | Wire mesh | Flexipac 1Y |
| Pressure (atm) | 1 | 1.6 |
| Rotor speed (rpm) | 200 | - |
| MEA concentration (wt%) | 30,55,65,75, 80 |
| Lean pump pressure (bar) | 2 |
| Rich pump pressure (bar) | 3 |
| Lean solvent temp (oC) | 40 |
| Heat exch. temp approach (oC) | 10 |

* + 1. Base process analysis

Process analysis of the large-scale PCC process investigates the influence of lean CO2 loading on capture level for MEA concentrations of 30 wt% - 80 wt%. Results in Figure 2 indicate a gradual decrease in the capture level as lean loading increases from 0.18 to 0.3 molCO2/molMEA for all the MEA concentrations.

Figure 2: Influence of lean loading on CO2 capture level

The energy consumed to rotate the RPB absorber at 200 rpm and 90% CO2 capture level and the energy consumed for solvent regeneration energy (GJ/tCO2) are shown in Figure 3.

Figure 3: Energy consumption for absorber rotation and regeneration

* + 1. Process optimisation

Process optimisation is performed to minimise the total energy consumption of the large-scale PCC process. Column internals, flue gas conditions and the operating conditions of pump and heat exchangers are kept constant for the optimisation. The details of the objective function and the constraints are shown below.

Objective:Minimise total energy consumption (Etotal) which is the sum of regeneration energy (Ereg) and absorber rotational energy (Erot, abs)

|  |  |
| --- | --- |
| $$E\_{total}=E\_{reg}+E\_{rot, abs}$$ | 5 |

Decision variables**:** lean solvent flow rate *(L)*, reboiler temperature (*Treb*), condenser temperature *(Tcond),* and absorber rotor speed *(ωabs).*

Constraints: Capture level (CO2,cap) and CO2 purity (CO2,purity)

|  |  |
| --- | --- |
| $$CO\_{2,cap}=90\%$$ | 6 |
|  |  |
| $$CO\_{2,purity}=96$$ | 7 |

The optimisation found a solution satisfying all the constraints and the results are shown in Table 3. The lowest total energy consumption of 4.46 GJ/tCO2 was found at an optimal MEA concentration of 75 wt%. At this MEA concentration, the rotational energy consumption of the RPB absorber is 0.47 GJ/tonCO2 while the regeneration energy consumption of the large-scale PCC process is 3.99 GJ/tCO2.

Table 3: Optimisation results at 30, 55, 65, 75 and 80 wt% MEA concentrations

|  |  |
| --- | --- |
| MEA conc. (wt%) | Objective value |
| Erot,abs (GJ/tCO2) | Ereg (GJ/tCO2) | Etot (GJ/tCO2) |
| 30 | 0.84 | 4.76 | 5.60 |
| 55 | 0.67 | 4.49 | 5.16 |
| 65 | 0.55 | 4.23 | 4.78 |
| 75 | 0.47 | 3.99 | 4.46 |
| 80 | 0.37 | 4.34 | 4.71 |

* 1. Conclusions and future work

A steady-state user-defined rate-based model of RPB absorber developed in ACM was validated at a pilot scale using experimental data and then scaled up to deal with flue gas from a 250 MW CCGT power plant. The large-scale RPB absorber model was exported from ACM to the Aspen Plus® environment. The RPB absorber was integrated with the PB stripper and other process equipment (pumps and heat exchangers) to develop the whole process for a large-scale PCC process. This large-scale model was used for process analysis and optimization studies. The lowest total energy consumption of 4.46 GJ/tCO2 was found at an optimal MEA concentration of 75 wt%. The regeneration energy contributed the largest share (3.99 GJ/tCO2) to the total energy consumption. Future will include economic assessments to determine the optimal concentration that results in the lowest CO2 capture cost.

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