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Preliminary Performance Assessment of Intensified Stripper in Post-combustion Carbon Capture through Modelling and Simulation

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Abstract

Intensified stripper used in chemical absorption process based on rotating packed bed (RPB) technology was studied through modelling and simulation in this paper. The model was developed by dynamically linking Aspen Plus® rate-based model with visual Fortran. Suitable correlations for RPB were implemented in Fortran to replace the default correlations in Aspen Plus® rate-based model. The standalone stripper model was validated with experimental data. The paper compared standalone intensified stripper with conventional stripper using MEA solvent. The result shows 9.69 times size reduction. Therefore PI has great potential for use in carbon capture application.

Keywords: Post-combustion CO_2 capture; MEA solvent; Process Intensification (PI); Rotating Packed Bed (RPB); Process simulation

1. Introduction

Environmental concern has posed many questions as to the impact of greenhouse gas to those changes currently noticed in world climate and the future dangers that will be expected if mitigation measures are not put in place. Combustion of coal and petroleum accounts for the majority of the anthropogenic CO_2 emissions. Albo *et al.* [2] stated that among the greenhouse gases, CO_2 contributes to more than 60% of global warming. Recent report by CO2-Earth [4] shows that as on 14 March 2016 CO_2 atmospheric concentration stood at 404.47 ppm, this increased atmospheric concentration of CO_2 affects the radiative balance of the earth surface [3].

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PCC for coal-fired power plants using conventional packed columns has been reported by many authors. Dugas [8] carried out pilot plant study of PCC in the context of fossil fuel-fired power plants. Lawal *et al.* [9-11] carried out dynamic modelling and process analysis of CO_2 absorption for PCC in coal-fired power plants. In all these studies, one of the identified challenges to the commercial roll-out of the technology has been the high capital and operating costs which has an unavoidable impact on electricity cost. Approaches such as heat integration and inter-cooling could reduce the operating cost slightly. However, they limit the plant flexibility and will make operation and control more difficult [12]. Process intensification (PI) has the potential to meet this challenge [13-15].

Study of intensified absorber was reported in Joel *et al* [16,17] and Agarwal *et al.* [18]. Joel *et al* [16] reported 12 times volume reduction for absorber if using RPB technology as compared to packed column while results from Agarwal *et al.* [18] indicated 7 times volume reduction if using RPB as compared to conventional packed column. The study by Joel *et al.* [16] uses aqueous MEA solvent while Agarwal *et al.* [18] uses diethanolamine (DEA) as solvent. This is the reason for the differences in size reduction since faster reaction rate means shorter residence time and slower reaction rate means longer residence time required for the same capture rate. Jassim *et al.* [19] reported experimental studies on intensified regenerator using RPB. Typical process flow diagram used in this paper is shown in Fig. 1

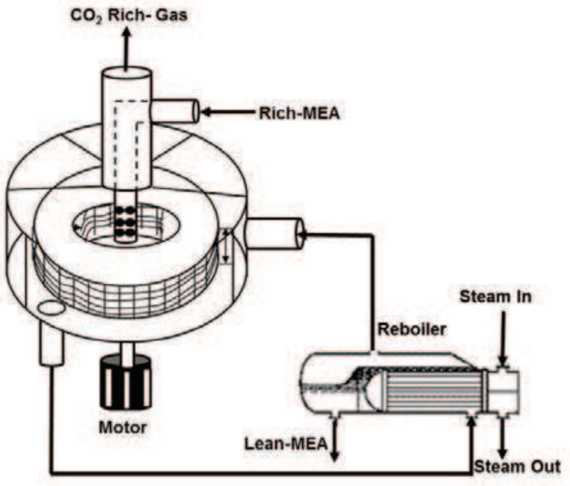

Figure 1 Schematic diagram of an RPB stripper

1.1. Motivation

Over 8,000 tonnes of CO_2 per day will be released from a typical 500 MWe supercritical coal fired power plant operating at 46% efficiency (LHV basis) [20]. Agbonghae et al. [21] reported that two absorbers and one stripper will be required for a 400 MWe gas fired combined cycle gas turbine (CCGT) power plant. The two absorbers having packing height 19.06 m and 11.93 m in diameter while the stripper has packing height 28.15 m and 6.76 m in diameter. These huge packed columns translate into high capital and operating costs. A significant amount of steam from power plants has to be used for solvent regeneration. This translates into high thermal efficiency penalty. Therefore, it is necessary to look for technological options that will reduce this energy requirement

1.2. Novel contribution

There are three novel aspects in this paper: (a) a new first principle model for intensified regenerator using RPB was developed which was implemented in Aspen Plus® rate-based model by replacing different correlations for mass transfer, interfacial area and liquid hold-up. (b) Steady state validation of the intensified regenerator is performed using experimental data from Jassim *et al.* [19]. (c) Comparison between RPB based intensified regenerator and PB based regenerator was performed.

2. Model development

Model for intensified regenerator using RPB does not exist in any commercially available model library (including Aspen Plus®). To model intensified regenerator using RPB, the default mass/heat transfer correlations in the Aspen Plus® rate-based model were replaced with subroutines written in Intel® visual FORTRAN. The new model now represents an intensified absorber/regenerator using RPB. The correlations include: liquid phase mass transfer coefficient given by Chen *et al.* [22], gas-phase mass transfer coefficient given by Chen [23], interfacial area correlation estimated by Luo *et al.* [24] and liquid hold-up correlation given by Burns *et al.* [25]. Dry pressure drop expression was used since it accounts in an additive manner of the drag and centrifugal forces, the gas-solid slip and radial acceleration effect [26].

Implementation procedures

The procedure used in this paper for modelling and simulation of the RPBs is shown in **Fig. 2**

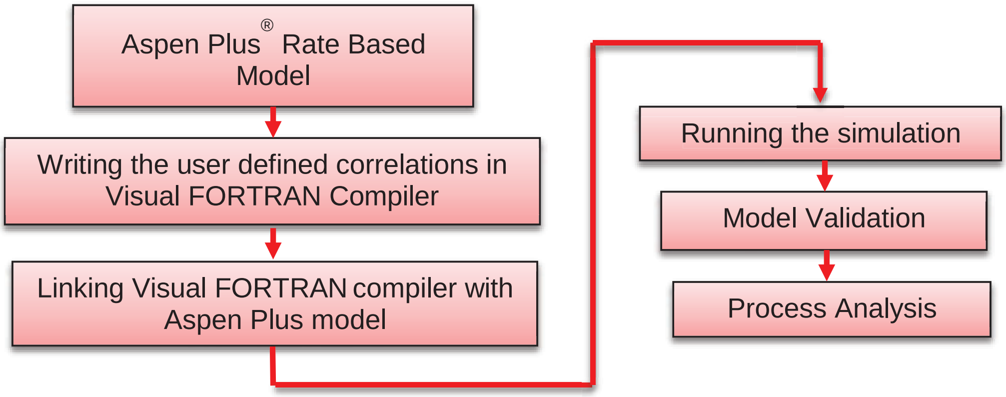

Figure 2 Methodology used in this paper [16,17]

3. Model validation

The experimental data used for the model validation was obtained from Jassim *et al.* [19]. From their experiments, MEA concentrations of 32.9 wt%, 35.7 wt%, 30.8 wt%, 57.4 wt% and 52 wt% were selected for the validation study. The equipment specification and process input conditions for the model validation study are shown in Tables 1 and 2. In this study, two different rotor speed conditions 800 rpm and 1000 rpm were used.

Table 1 RPB stripper packing specifications used by Jassim et al. [19]

Description	value
RPB outer diameter	0.398 m
RPB inner diameter	0.156 m
RPB axial depth	0.025 m
Packing specific surface area	2132 m^2/m^3
Packing void fraction (i.e. porosity)	0.76

Table 2 Input process conditions for Run 1 to Run 5 [19]

	Runs				
	Run 1	Run 2	Run 3	Run 4	Run 5
Rotor speed (RPM)	800	800	800	1000	1000
Rich-MEA temperature (ºC)	67.1	69	70	57.2	58.4
Rich-MEA pressure (atm.)	1	1	1	1	1
Rich-MEA flow rate (kg/s)	0.2	0.2	0.4	0.4	0.2
Rich-MEA composition (wt. %)					
H_2O	58.116	54.013	61.536	25.142	32.895
CO_2	8.984	10.287	7.664	17.458	15.105
MEA	32.900	35.700	30.800	57.400	52.000
Rich-MEA CO_2 loading (mol CO_2 /mol MEA)	0.3790	0.3999	0.3454	0.4221	0.4030
Steam rate (kg/s)	0.072	0.069	0.072	0.069	0.072

Table 3 Simulation results compared to experimental data [19] for Run 1 to Run 5

	Runs				
	Run 1	Run 2	Run 3	Run 4	Run 5
Rotor speed (RPM)	800	800	800	1000	1000
Experimental measurement					
Lean-MEA CO_2 loading (mol CO_2/mol MEA)	0.321	0.329	0.329	0.403	0.334
Model prediction					
Lean-MEA CO_2 loading (mol CO_2/mol MEA)	0.316	0.295	0.298	0.355	0.320
Relative error (%)	1.558	10.334	9.422	11.911	4.192

Model validation results are shown in Table 3 which gives percentage error prediction of not more than 12 % on the lean-MEA CO_2 loading. The lean-MEA CO_2 loading was evaluated on mole basis. In summary, the model has predicted all experimental data reasonably well with not more than 12% error prediction, the model developed can then be use to carry out process analysis in order to study the process behaviour when there is a change in any variables.

4. Comparison between RPB based intensified regenerator and PB based regenerator

This study was carried out to provide a comparison under some fixed conditions such as Rich-MEA flowrate, pressure, temperature, rich-MEA loading and lean-MEA loading between intensified regenerator and conventional regenerator. Table 4 is used as the input conditions for the conventional and intensified regenerator. The rotor speed for the intensified regenerator is kept constant at 1000 rpm. Regeneration efficiency was kept constant at 37.16 % for both the conventional and the intensified regenerators.

Table 4 Process conditions for Conventional and RPB regenerator

Description	Conventional regenerator	RPB regenerator
	Rich-MEA	Rich-MEA
Rich-MEA temperature (ºC)	97	97
Rich-MEA pressure (atm.)	2	2
Rich-MEA flowrate (kg/s)	0.300	0.300
Rich-MEA loading	0.482	0.482
(mol CO_2/mol MEA)		
Mass-Fraction (%)		
H_2O	58.116	58.116
CO_2	8.984	8.984
MEA	32.900	32.900

Table 5 Comparison between conventional and RPB stripper

Description	Conventional regenerator	RPB regenerator
Height of packing (m)	3.700	0.371 (r_o)
		0.152 (r_i)
diameter (m)	0.476	0.167 axial depth
Packing Volume (m^3)	0.659	0.015
Packing volume reduction		44 times
Volume of unit (m^3)	0.659 [a]	0.068[b]
Volume reduction factor		9.691 times
Specific area (m^2/m^3)	151	2132
Void fraction	0.980	0.760
Lean-MEA loading (mol CO_2/mol MEA)	0.303	0.303

[a] Excluding sump
[b] Using the assumption given by Agarwal et al [18]

The study in Table 5 showed 44 times packing volume reduction in an intensified regenerator compared to conventional packed column regenerator without sumps. By using the assumption given by Agarwal *et al.* [18] that the casing volume of RPB is 4.5 times the rotating packing volume, then volume reduction compared to conventional packed column regenerator is found to be 9.69 times smaller. The height of transfer unit (HTU) for conventional packed column regenerator is calculated as 20.8 cm while for the intensified regenerator is 1.7 cm. The smaller HTU in RPB regenerator is responsible for smaller RPB regenerator size compared to conventional packed column.

5. Conclusions

Intensified stripper using RPB technology was modelled in this study. The steady state model was implemented by linking Aspen Plus® and visual FORTRAN. The standalone model developed was validated with experimental data reported in Jassim *et al.* [19]. The model validation shows good agreement with the experimental data. Under same process condition there is 9.69 times reduction in volume for intensified stripper compared to conventional packed column. This reduction can lead to a decrease in capital investment.

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References

[1] Albo J, Luis P, Irabien A. Carbon dioxide capture from flue gases using a cross-flow membrane contactor and the ionic liquid 1-ethyl-3-methylimidazolium ethylsulfate. Ind Eng Chem Res 2010;49:11045-51.

[2] CO2-Earth. Daily CO_2: Mauna Loa Observatory/ Atmospheric CO_2 Concentration
. Available at: https://www co2 earth/daily-co2 (accessed March, 2016).

[3] World Meteorological Organization (WMO). Press Release No. 991
. 26 May 2014;http://www.wmo.int/pages/mediacentre/press_releases/pr_991_en.html (accessed June, 2014).

[4] Dugas RE. Pilot plant study of carbon dioxide capture by aqueous monoethanolamine. MSE Thesis, University of Texas at Austin 2006.

[5] Lawal A, Wang M, Stephenson P, Obi O. Demonstrating full-scale post-combustion CO_2 capture for coal-fired power plants through dynamic modelling and simulation. Fuel 2012;101:115-28.

[6] Lawal A, Wang M, Stephenson P, Koumpouras G, Yeung H. Dynamic modelling and analysis of post-combustion CO_2 chemical absorption process for coal-fired power plants. Fuel 2010;89:2791-801.

[7] Lawal A, Wang M, Stephenson P, Yeung H. Dynamic Modeling and Simulation of CO_2 Chemical Absorption Process for Coal-Fired Power Plants. Computer Aided Chemical Engineering 2009;27:1725-30.

[8] Kvamsdal H, Jakobsen J, Hoff K. Dynamic modeling and simulation of a CO_2 absorber column for post-combustion CO_2 capture. Chemical Engineering and Processing: Process Intensification 2009;48:135-44.

[9] Reay D. The role of process intensification in cutting greenhouse gas emissions. Appl Therm Eng 2008;28:2011-9.

[10] Wang M, Lawal A, Stephenson P, Sidders J, Ramshaw C. Post-combustion CO_2 capture with chemical absorption: A state-of-the-art review. Chem Eng Res Design 2011;89:1609-24.

[11] Wang M, Joel AS, Ramshaw C, Eimer D, Musa NM. Process intensification for post-combustion CO2 capture with chemical absorption: A critical review. Appl Energy 2015;158:275-91.

[12] Joel AS, Wang M, Ramshaw C, Oko E. Process analysis of intensified absorber for post-combustion CO_2 capture through modelling and simulation. International Journal of Greenhouse Gas Control 2014;21:91-100.

[13] Joel AS, Wang M, Ramshaw C. Modelling and simulation of intensified absorber for post-combustion CO_2 capture using different mass transfer correlations. Appl Therm Eng 2015;74:47-53.

[14] Agarwal L, Pavani V, Rao D, Kaistha N. Process intensification in HiGee absorption and distillation: design procedure and applications. Ind Eng Chem Res 2010;49:10046-58.

[15] Jassim MS, Rochelle G, Eimer D, Ramshaw C. Carbon dioxide absorption and desorption in aqueous monoethanolamine solutions in a rotating packed bed. Ind Eng Chem Res 2007;46:2823-33.

[16] BERR. Advanced power plant using high efficiency boiler/turbine. Report BPB010. BERR, Department for Business Enterprise and Regulatory Reform. 2006;Available at: http://webarchive.nationalarchives.gov.uk/20090609003228/http://www.berr.gov.uk/files/file30703.pdf (accessed August 2015).

[17] Agbonghae EO, Hughes KJ, Ingham DB, Ma L, Pourkashanian M. Optimal Process Design of Commercial-Scale Amine-Based CO_2 Capture Plants. Ind Eng Chem Res 2014;53:14815-29.

[18] Chen Y, Lin F, Lin C, Tai CY, Liu H. Packing characteristics for mass transfer in a rotating packed bed. Ind Eng Chem Res 2006;45:6846-53.

[19] Chen Y. Correlations of mass transfer coefficients in a rotating packed bed. Ind Eng Chem Res 2011;50:1778-85.

[20] Luo Y, Chu G, Zou H, Zhao Z, Dudukovic MP, Chen J. Gas–liquid effective interfacial area in a rotating packed bed. Ind Eng Chem Res 2012;51:16320-5.

[21] Burns J, Jamil J, Ramshaw C. Process intensification: operating characteristics of rotating packed beds—determination of liquid hold-up for a high-voidage structured packing. Chemical Engineering Science 2000;55:2401-15.

[22] Llerena-Chavez H, Larachi F. Analysis of flow in rotating packed beds via CFD simulations—Dry pressure drop and gas flow maldistribution. Chemical Engineering Science 2009;64:2113-26.