

Intensification of CO₂ Capture from Methane-rich Streams Using a Rotating Packed Bed Absorption Column

J.G.V.G. Mendes^a, G. Simões^a, D.M. Santana^b, S.A.B. Vieira de Melo^{b,c}, K.V. Pontes^{b,*}, M. Illner^d, E. Esche^d, J.-U. Repke^d

^a Departamento de Engenharia Química, Escola Politécnica, Universidade Federal da Bahia, Rua Aristides Novis, 2, Federação, Salvador, Bahia 40210-630, Brazil

^b Programa de Pós-Graduação em Engenharia Industrial, Escola Politécnica, Universidade Federal da Bahia, Rua Aristides Novis, 2, Federação, Salvador, Bahia 40210-630, Brazil

^c Centro Interdisciplinar em Energia e Ambiente, Campus Universitário da Federação/Ondina, Universidade Federal da Bahia, Rua Barão de Jeremoabo, S/N, Ondina, Salvador, Bahia 40170-115, Brazil

^d Process Dynamics and Operations Group, Technische Universität Berlin, D-10623 Berlin, Germany

* Corresponding author: karenpontes@ufba.br

Abstract. The natural gas produced in the Brazilian pre-salt reservoirs contains a large amount of CO₂ (up to 40%), which has to be removed offshore to prevent pipeline corrosion during transport and because of a national regulation that requires at most 3% of CO₂ in the natural gas for its commercialization. The space limitations in off-shore platforms require intensifying CO₂ capture. An alternative is the chemical absorption in the Rotating Packed Bed (RPB). This paper aims to develop a mathematical model for the RPB attempting to investigate its use for the CO₂ capture from methane-rich streams using amines. The RPB is modeled in Aspen Plus, using the embedded rate-based module, but linked to user-defined correlations in Fortran to compute mass transfer correlations and interfacial area as a function of the centrifugal acceleration and the radius. To properly describe phase and chemical equilibrium in the rate-based approach, eNRTL model was used. The RPB model predictions were compared with experimental data from the literature for CO₂ capture and average deviations of around 4.9% were observed indicating that the modified rate-based model can satisfactorily capture the behavior of the RPB. Sensitivity analysis identified that the carbon capture level is mostly influenced by the lean amine concentration, flowrate, and temperature. For typical concentrations of natural gas streams, lean amine concentration higher than 45% indicates saturation of capture capacity.

All rights reserved by the authors as per DA2022 copyright notice.

Keywords modeling and simulation; CO₂ capture; chemical absorption; process intensification; RPB – Rotating Packed Bed.

Introduction

Brazil is the eighth largest oil producer worldwide thanks to the pre-salt reservoirs found in deep-sea areas, which extend for 800 km along the Brazilian coast. The associated gas has a high concentration of CO₂ (20-45%), which cannot be emitted into the atmosphere due to environmental reasons. Therefore, oil and gas extraction and production companies separate CO₂ offshore to prevent pipeline corrosion during transport and because of a national regulation that requires up to 3% of CO₂ in the natural gas for its commercialization. Removing the CO₂ from CO₂-rich natural gas streams is a technical challenge that could further allow the exploration of mature natural gas reservoirs with high CO₂ content around the world, either onshore or offshore.

The most common and mature carbon capture process is chemical absorption with an amine solution, as it is a low-risk technology and is considered promising in the short term for large-scale capture (Joel et al., 2014). This process commonly takes place in conventional packed bed (PB) columns, where the main limitations are the large equipment size, which translates into high costs of installation and operation, and the high energy costs for solvent recovery. Due to space limitations in offshore FPSO (Floating Production Storage and Offloading) units, though, membranes are usually considered to separate the CO₂ from the natural gas. Process intensification is an alternative to promote carbon capture more efficiently and economically.

The Rotating Packed Bed (RPB) column, a HiGee technology, is an example of process intensification applied in carbon capture by chemical absorption. While gravity is the driving force for the liquid phase flow in a conventional column, in an RPB the bed rotation creates centrifugal fields up to 1000 times stronger, potentializing the mass transfer in the equipment, and consequently, enhancing the CO₂ capture. Compared to conventional columns, the mass transfer efficiency in RPB makes the volume and weight of the equipment significantly smaller and the operational limits of flooding are higher (Borhani et al., 2018). Thus, the industrial application of RPB to purify gases from industrial activities is advantageous compared to the conventional column, aiming at reducing GHG emissions.

For the development and improvement of this technology, experimental research and computer simulation are fundamental, helping in process analysis, optimization, scale-up, etc. (Borhani et al., 2018). Table 1 shows some studies reported in the literature regarding the modeling and simulation of the chemical and physical absorption processes with the RPB. Chemical absorption with the RPB is usually considered in post-combustion capture processes, described by low CO₂ partial pressures. Bernardes (2018) designed an RPB for capturing CO₂ from natural gas in an off-shore platform in the Brazilian pre-salt, however, they considered the physical absorption of CO₂, using propylene carbonate as a solvent. In reviewing the challenges of enhanced absorption for natural gas treatment, Tay et al. (2019) reported that the RPB proves to be an advantageous technology in terms of process intensification, but that maintenance costs and energy consumption must still be minimized. Chemical absorption in RPBs to purify natural gas streams with high partial pressures of CO₂ has not yet been satisfactorily covered in the literature. Therefore, there is still a need for further advances and development of research on this topic to ascertain if the RPB is suited for this application. Due to the fact that this technology makes it possible to capture CO₂ more efficiently in smaller equipment, the RPB becomes extremely attractive for capturing CO₂ in the treatment of off-shore natural gas, where space is a scarce resource. Thus, the aim of this paper is to model and simulate the chemical absorption in an RPB to treat natural gas streams with high CO₂ partial pressures and also evaluate the influence of critical variables.

Table 1.
Literature review on modeling and simulation of RPB for CO₂ capture.

Reference	Description	Solvent
Yu <i>et al.</i> (2012)	Mathematical model of chemical absorption considering series of stirred tanks. Validated with experimental data with 10% molar fraction of CO ₂ in the feed gas.	MEA, DETA and PZ with different concentrations.
Joel <i>et al.</i> (2014)	Simulation of chemical absorption using Aspen Plus® with integrated subroutines to determine the mass transfer coefficient. Validated with experimental data from Jassim (2002) and Jassim et al. (2007).	MEA at 55 to 75% weight.
Kang <i>et al.</i> (2014)	Modeling the mass transfer coefficients of chemical absorption in gPROMS®, which was integrated with Aspen Properties® through the CAPE-OPEN interface. Validated with experimental data from Yu et al. (2012) and Jassim et al. (2007).	MEA at 30 to 75% weight.
Joel <i>et al.</i> (2015)	Comparison of different correlations for mass transfer coefficients for the chemical absorption. Aspen Plus® was integrated with subroutines to determine the mass transfer coefficient as in Joel et al. (2014).	MEA at 55 to 75% weight.
Kang <i>et al.</i> (2016)	Modeling chemical absorption in conventional and RPB columns in gPROMS®. Validated with their own experimental data and from Jassim et al. (2007).	MEA at 30% weight and NH ₃ at 3% weight.
Thiels <i>et al.</i> (2016)	Comparison of chemical absorption in conventional and RPB column for carbon capture using Aspen Custom Modeler®. Validated with their own experimental data and from Jassim et al. (2007).	MEA at 30% weight.
Bernardes <i>et al.</i> (2018)	Simulation of physical absorption in RPB for natural gas treatment in the Brazilian pre-salt using Aspen Plus® integrated with subroutines. Validated by theoretical sensitivity analysis.	Propylene carbonate as physical solvent.
Borhani <i>et al.</i> (2018)	Modeling of chemical absorption in gPROMS®. Validated with experimental data from Jassim (2002) and Jassim et al. (2007). The rotation speed has the greatest effect on CO ₂ capture.	MEA at 55 to 75% weight.

Model Development

The countercurrent RPB was modeled in Aspen Plus® using the embedded *RadFrac* module with the rate-based model, which describes not only the thermodynamic equilibrium but also the hydrodynamics of a conventional packed-bed column. Although the software database offers several mass transfer correlations, none of them allow the user to replace the gravitational force by the centrifugal acceleration neither include the radius dependence of the interfacial area and the spatial velocities, as required to represent the RPB. To this end, the mass transfer correlations, the gas-

liquid interfacial area as well as the liquid hold up, summarized in Table 2, were implemented in a Fortran subroutine and linked to Aspen Plus® using a dynamic-link library (DLL). The acceleration generated by the centrifugal field ($g_c = r_x \omega^2$) overrides the gravitational acceleration ($g_c = 9.81 \text{ m/s}^2$) in the dimensionless number of Grashof (Gr) and Froude (Fr). When using the *RadFrac* module, the column height is estimated as the difference between the outer and inner radius of the RPB (Joel *et al.*, 2014), and the column diameter is equivalent to the axial length of the intensified column, H . The column radius is discretized as pieces of cake with increasing size through computing the cross-sectional area in the sub-routine as $2\pi\bar{r}H$, where $\bar{r}$ is the average radius of the discretized segment. As a consequence, the dimensionless numbers (Reynolds, Froude, Grashof, Webber), the spatial velocities and the interfacial area change with the radius accordingly. Yu *et al.* (2012) considered the set of correlations in Table 2 when modeling the RPB and validated the results with an average deviation of 11.7% against experimental data to capture CO₂ from a feed stream of N₂ with 10% mol of CO₂. Joel *et al.* (2014) also considered this set of correlations and validated the proposed model against the experimental data from Jassim *et al.* (2002) with an average deviation of 4.8% and maximum deviation of 11.9% for a gas stream with CO₂ mole fraction ranging between 3.6 and 4.7%, lean amine flow rate at 0.66 and 0.35 kg/s, and MEA concentration at 55 and 76 % wt.

Table 2.
Mass transfer correlations.

Reference	Correlation
Gas phase mass transfer Onda <i>et al.</i> (1968)	$k_{g,i} = 2 (Re_g)^{0.7} (Sc_{g,i})^{1/3} \left(\frac{D_{g,i}}{a_p d_p^2} \right)$
Liquid phase mass transfer Tung and Mah (1985)	$k_{l,i} = 0.92 \left(\frac{a_p}{a_{gl}} \right)^{1/3} (Re_l)^{1/3} (Sc_{l,i})^{0.5} (Gr_l)^{1/6} \left(\frac{D_{l,i}}{d_p} \right)$
Gas-liquid interfacial area Onda <i>et al.</i> (1968)	$\frac{a_{gl}}{a_p} = 1 - \exp \left(-1.45 \left(\frac{\sigma_c}{\sigma} \right)^{0.75} (Re_l)^{0.1} (Fr_l)^{-0.05} (We_l)^{0.2} \right)$
Liquid hold up Burns <i>et al.</i> (2000)	$\varepsilon_L = 0.039 \left(\frac{g_c}{g_0} \right)^{0.5} \left(\frac{U}{U_0} \right)^{0.6} \left(\frac{v}{v_0} \right)^{0.22}$

Although different alkanolamine solutions have been investigated for CO₂ absorption, monoethanolamine (MEA) and N-methyl-diethanolamine (MDEA) have been recommended in the literature to separate CO₂ from natural gas streams due to the high CO₂ concentrations and high pressures (Liu *et al.*, 2019; Shahid *et al.*, 2021). The kinetics of CO₂ absorption into MEA and MDEA were taken from Ramachandran *et al.* (2006). Aspen rate-based module can model reactions occurring in the film, therefore enhancement factors for film reactions are not needed. To describe the phase equilibrium and to calculate physical properties, the electrolyte Non-Random Two-Liquid (e-NRTL) was considered. It is the most commonly used thermodynamic model to describe the phase equilibrium in a system of CO₂ capture with amine, as several studies in the literature show (Joel *et al.*, 2014; Kang *et al.*, 2014; Kang *et al.*, 2016; Liu *et al.*, 2019). In addition, this model was validated by Aspen Technology (2014) for the MEA-MDEA-CO₂-H₂O system with satisfactory accuracy against experimental data.

The chemical absorption in PB columns for natural gas sweetening with MEA and MDEA has been reported in the literature (Liu *et al.*, 2019; Shahid *et al.*, 2021) but, up to the authors' knowledge, no data have been reported when using RPB. Therefore, as a first step to validate the kinetics and thermodynamics of the methane rich system, a conventional packed absorption column to treat natural gas was simulated in Aspen Plus® using the rate-based model. This PB model was validated with the data from Liu *et al.* (2019), who approached the CO₂ separation from associated gas (20% CO₂ and 80% CH₄) in a mature petroleum reservoir in China. The Brf-85 (Bravo *et al.*, 1985) correlation was used for the mass transfer and interfacial area, and the column was packed with *MELLAPAK*. The column height was discretized into 20 segments. The inlet gas flow rate is 4 ton/h, while the solvent contains roughly 4% mol MEA and 7% mol MDEA. Secondly, the RPB model itself was validated with experimental data from Jassim (2002), as reported in Borhani *et al.* (2018), in a pilot plant to treat a gas stream with 3 to 5% molar fraction of CO₂ (82.4 kg/h @ 4.4% mol CO₂) at 2.87 kmol/h with lean-MEA concentrations at 55 and 75% wt (28% and 39% mol). The lean-MEA high concentration seeks to maximize CO₂ absorption rate while minimizing corrosion problems (Joel *et al.*, 2014). The pilot RPB has external and internal radius of 0.199 and 0.078 m, respectively, and axial length of 0.166 m. The column was packed with coil with effective area of 2.132 m²/m³ and void fraction of 0.76. The adjustment factor of the interfacial area was set to 0.35, and the adjustment factor of the reaction, at 0.5. The packing was discretized

into 7 segments, since a greater number of segments did not demonstrate a relevant difference in the accuracy of the model. The capture efficiency is evaluated by the Carbon Capture Level (*CCL*), defined by:

$$CCL = \frac{y_{CO_2}^{in} - y_{CO_2}^{out}}{y_{CO_2}^{in}}$$

where $y_{CO_2}^{in}$ is the molar fraction of CO₂ in the gaseous feed stream and $y_{CO_2}^{out}$ out is the molar fraction of CO₂ in the gaseous output stream.

After validating the RPB model, a sensitivity analysis was carried out to investigate the effect of inlet variables on the carbon capture level. Table 3 summarizes the considered scenarios, where 1 to 3 regard the exhaust gas and 4, the natural gas. The lean-amine contains MEA, water, and traces of CO₂ as the solvent should be regenerated in desorption. When extrapolating the model to simulate the natural gas feed, the inlet feed gas composition is changed to 20% mol CO₂ and 80% mol CH₄, which is the composition adopted by Liu *et al.* (2019) but with a molar flow rate of 2.87 kmol/h for a fair comparison with the other Scenarios. Since the natural gas produced in the Brazilian pre-salt reservoirs contains a large amount of CO₂, the Scenario 4 investigates the effect of increasing the CO₂ concentration, as well as the lean-MEA concentration, on the *CCL*. To ascertain the equivalent volume of a conventional packed absorption column to achieve the same *CCL*, Scenario 4 was considered the base case but with MEA concentration at 75% wt and CO₂ feed concentration at 20%. The PB column diameter was kept at 0.166 m, which is equivalent to the RPB axial length. The packing height of the PB column was then increased until the *CCL* reached the same value of the RPB.

Table 3.
Scenarios for sensitivity analysis.

Variables	Scenario			
	# 1	# 2	# 3	# 4
Bed Rotation (rpm)	400 – 1200	400 – 1200	600	1200
Lean-MEA temperature (°C)	15 – 50	20	20	20
Lean-MEA concentration (wt%)	56.5 and 77	56.5 and 77	30 – 75	30 – 75
CO ₂ concentration in lean amine (wt%)	3.09 and 2.17	3.09 and 2.17	6.86 – 2.8	6.86 – 2.80
Lean-MEA flow rate (kg/s)	0.35	0.2 – 0.8	0.35	0.35
CO ₂ composition in feed gas (mol%)	4.4	4.4	2.5 – 50	20 – 60

Results and Discussion

The model representing the PB column was validated with the data simulated by Liu *et al.* (2019). Here an average relative deviation of 2.3% and maximum deviation of 4.6% were observed, whereas Liu *et al.* (2019) reported deviations up to 3% compared to experimental data. This result indicates that the model of the conventional column for the capture of CO₂ from associated gas is representative and might be used as a basis for the development of the RPB model. After linking the DLL with the corresponding correlations in Table 2 for the RPB and setting the operating conditions according to Jassim (2002), the predictions of the RPB model were compared with the experimental data from Jassim (2002). The average relative deviation observed was 4.9% and the maximum, 12.3%. These results are in accordance with Joel *et al.* (2014), who modeled an RPB in Aspen Plus® with integrated subroutines to compute user-defined correlations for the RPB, as proposed here, and validated the model against the experimental data from Jassim (2002). Therefore, the RPB absorber model developed in Aspen Plus can reasonably capture the behavior of the pilot plant absorber and can be used to investigate the performance of the process at different operating conditions.

Figure 1 illustrates the results of Scenarios 1 and 2 of the sensitivity analysis. The *CCL* is plotted against the lean-amine feed temperature and flow rate. The speed of rotation is distinguished by lines with different colors, and the lean-MEA concentration is indicated by dashed lines: solid lines correspond to 56.5% wt, whereas dotted lines correspond to 77% wt. The increase in *CCL* due to lean-amine temperature is associated with the enhanced kinetics and the reduced viscosity of the liquid phase. As temperature increases, the less viscous liquid causes a reduction in the gas-liquid film thickness and, consequently, enhances the mass transfer since absorption of CO₂ into alkanolamines solutions is a liquid film-controlled process (Jassim *et al.*, 2007; Joel *et al.*, 2014). The lean flow rate has a pronounced impact on the *CCL*, both due to the reaction as a consequence of excess of MEA, and due to the hydrodynamic effect. A higher flow rate increases the space velocity of the liquid phase, providing greater turbulence to the liquid flow and impacting the gas-liquid interface area, thus increasing the mass transport. The shape of the curve indicates that a further increase in lean flow rate might no longer be economically profitable because there will be a considerable

energy penalty for pumping and regenerating a higher flow of amine, without a significant benefit in the *CCL*. Regarding the effect of the acceleration of the centrifugal field, it increases the gas-liquid interface area because more droplets are formed, promoting the carbon capture. Regarding the effect of lean-MEA concentration, a more concentrated solution results in higher degree of CO₂ absorption because the reaction rate is a pseudo-first-order function of MEA concentration (Joel *et al.*, 2014; Freguia and Rochelle, 2003).

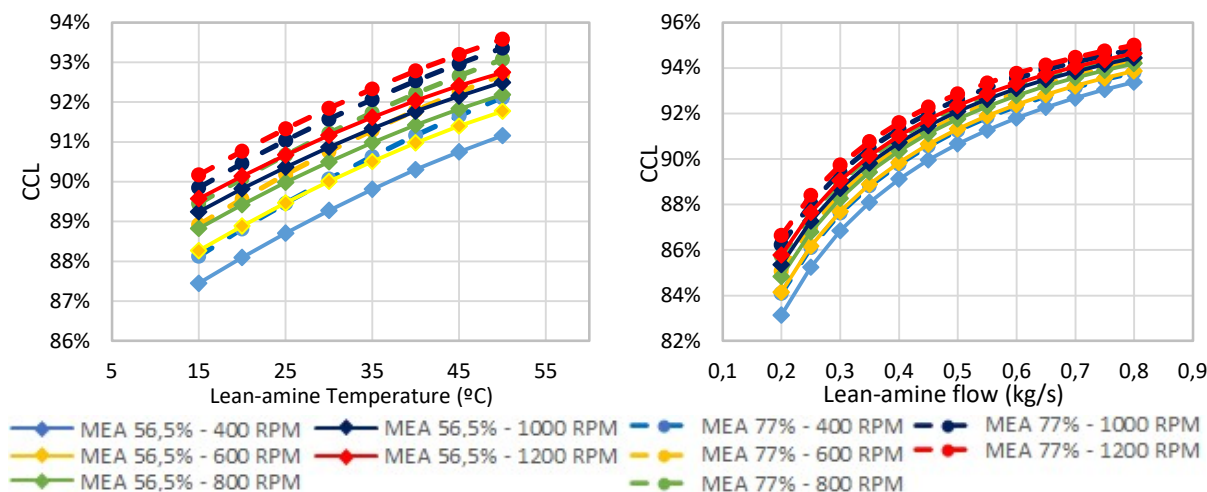


Fig. 1 Sensitivity Analysis regarding temperature (left) and mass flow (right) of lean amine solution at different levels of bed rotation and MEA concentration.

The effect of the CO₂ composition in the feed gas and the lean-MEA concentration is investigated in Scenario 3, and the result is illustrated in Figure 2(a). Both rotation levels (600 and 1000 rpm) presented similar behavior, therefore only the results for 600 rpm are illustrated. The *CCL* slightly increases as CO₂ mole fraction increases but, at low MEA concentrations, the absorption capacity saturates because MEA becomes the limiting reactant. For more concentrated lean-MEA solutions, though, the *CCL* is not sensitive to CO₂ composition in feed gas, indicating that MEA is in excess. It is important to highlight that the experimental data used for validating the model were run for lean-MEA concentrations between 55 and 75% wt, and a feed gas with 3 to 5% molar fraction of CO₂. Although the results in Figure 2(a) are an extrapolation of the model, they are in accordance with the theoretical expectation of the system. The model was then used to simulate the CO₂ capture from natural gas stream in Scenario 4 at 1200 rpm and the result is illustrated in Figure 2(b). The *CCL* is strongly influenced as CO₂ concentration increases for lower concentrations of lean-MEA, but no significant change is observed for concentrations greater than 45% wt, indicating that MEA tends to excess. The packing volume to capture CO₂ from natural gas at a rate of 2.87 kmol/h in an RPB was calculated at 0,017 m³, while the equivalent packing volume of the conventional column was 82% greater to meet the same *CCL* of 91,9%.

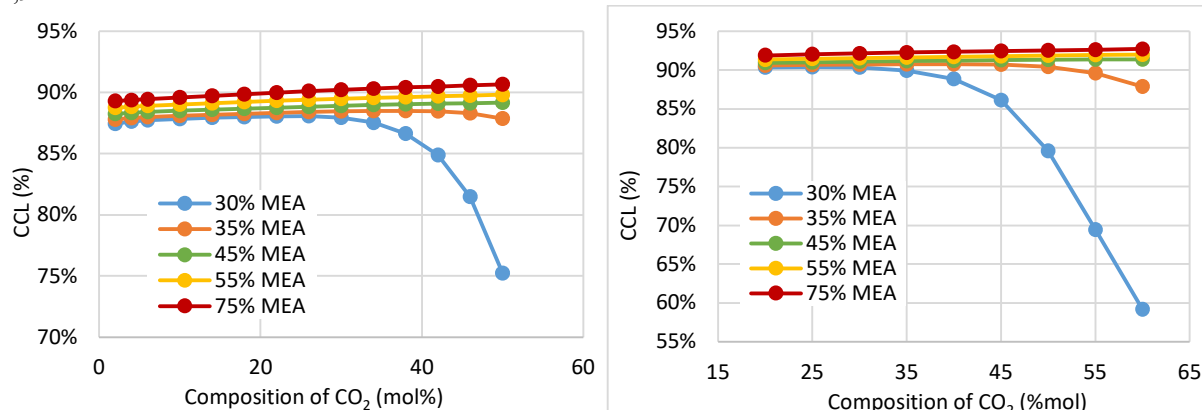


Fig. 2 Sensitivity analysis regarding CO₂ feed composition for (left) exhaust gas (600 rpm) and (right) natural gas at different levels of lean-amine concentration (1200 rpm).

Conclusion

The model developed in this work for the RPB was validated with experimental data from literature and is able to predict the CO₂ capture performance for the range it was validated. As the literature is scarce on experimental and simulated data regarding capture from natural gas with high CO₂ partial pressure, this study extrapolated the investigation range in a sensitivity analysis. As CO₂ concentration increases, less concentrated lean-MEA solutions cannot provide a satisfactory capture level. If natural gas with 20% CO₂ is to be treated, 45% wt lean-MEA should be used to provide a capture level of 90.9%, and more concentrated MEA solutions do not improve significantly the process performance. The RPB afforded a packing reduction of 82% compared to the traditional column, indicating the advantage of its use when space limitation is a concern, as in offshore platforms. These results indicate that further experimental studies on the use of RPB to capture CO₂ from natural gas streams are required to quantitatively validate the findings here discussed. Finally, models for RPBs for desorption are required to proceed towards process design.

References

1. Aspen Technology Inc., *Rate-Based Model of the CO₂ Capture Process by MEA+MDEA Aqueous Solution using Aspen Plus*, 2014.
2. Bernardes J.A.F. *Simulação e Dimensionamento de uma Coluna de Absorção Não Convencional para Captação de CO₂*. Dissertação de Mestrado. Universidade Estadual de Campinas. SP. 2018.
3. Borhani T.N.G., Oko E., Wang M., *Process modelling and analysis of intensified CO₂ capture using monoethanolamine (MEA) in rotating packed bed absorber*, Journal of Cleaner Production, 2018, 204.
4. Bravo J.L., Rocha J.A., Fair J.R. Mass transfer in Gause Packings. Hydrocarbon Process, 1985.
5. Burns J.R., Jamil, J.N., 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.
6. Freguia S., *Modeling of CO₂ Removal from Flue Gases with Monoethanolamine*, MS Thesis, The Univ. of Texas at Austin, 2002.
7. Freguia, S., Rochelle, G.T., 2003. *Modeling of CO₂ capture by aqueous monoethanolamine*. AIChE Journal 49 (7), 1676–1686.
8. Jassim M.S., *Process Intensification: Absorption and desorption of carbon dioxide from monoethanolamine solutions using HIGEE technology*, PhD Thesis, University of Newcastle upon Tyne, UK, 2002.
9. Jassim M.S., 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.
10. Joel A.S., Wang M., Ramshaw C., *Modelling and simulation of intensified absorber for post-combustion CO₂ capture using different mass transfer correlations*, Applied Thermal Engineering, 2015.
11. Joel A.S., Wang M., Ramshaw C., Oko E. *Process analysis of intensified absorber for postcombustion CO₂ capture through modelling and simulation*, International Journal of Greenhouse Gas Control, 2014, 21, 91-100.
12. Kang J.-L., Sun K., Wong D.S.-H., Jang S.-S., Tan C.-S., *Modeling studies on absorption of CO₂ by monoethanolamine in rotating packed bed*, International Journal of Greenhouse Gas Control, 2014, 25, 141-150.
13. Kang J.-L., Wong D.S.-H., Jang S.-S., Tan C.-S., *A comparison between packed beds and rotating packed beds for CO₂ capture using monoethanolamine and dilute aqueous ammonia solutions*, International Journal of Greenhouse Gas Control, 2016, 46, 228-239.
14. Liu B., Zhang M., Whang T., Jia W., *Process simulation of CO₂ capture from CO₂-EOR associated petroleum gas with aqueous MEA and MDEA solvents*, Energy Science and Engineering, 2019, 663-675.
15. Onda K., Takeuchi H., Okumoto Y. *Mass transfer coefficients between gas and liquid phases in packed columns*, J. Chem. Eng. Jpn, 1968, 1, 56-62.
16. Ramachandran N., Aboudheir A., Idem R., Tontiwachwuthikul P. Kinetics of the Absorption of CO₂ into Mixed Aqueous Loaded Solutions of Monoethanolamine and Methyldiethanolamine. Ind. Eng. Chem. Res. 2006, 45.
17. Shahid M., Z., Maulud A., S.; Bustam M.A., Suleman H., Halim H.N.A., Shariff A.M. Packed column modelling and experimental evaluation for CO₂ absorption using MDEA solution at high pressure and high CO₂ concentrations. Journal of Natural Gas Science and Engineering, 2021, 88
18. Thiels M., Wong D.S.H., Yu C.-H., Kang J.-L., Jang S.S., Tan C.-S. *Modelling and Design of Carbon Dioxide Absorption in Rotating Packed Bed and Packed Column*. International Federation of Automatic Control. 2016.
19. Tung H.-H. and Mah R.S.H., *Modelling liquid mass transfer in hige separation process*, Chemical Engineering Communications, 1985, 39, 147-153.
20. Yu, C.-H., Cheng, H.-H., Tan, C.-S. *CO₂ capture by alkanolamine solutions containing diethylenetriamine and piperazine in a rotating packed bed*. International Journal of Greenhouse Gas Control., 2012, 9, 136-147.