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Effect of Packing Structure on CO_2 Capturing Process

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The increasing concentration of carbon dioxide (CO_2) in the atmosphere is a primary global environmental concern due to its detrimental impacts on climate change. A significant reduction in CO_2 generation together with its capture and storage is an imperative need of the time. CO_2 can be captured from power plants and other industries through various methods such as absorption, adsorption, membranes, physical and biological separation techniques. The most widely used systems are solvent based CO_2 absorption method. The aim of this study was to analyze the effect of various random and structured packing materials in absorption column on CO_2 removing efficiency. Aspen plus was used to develop the CO_2 capture model for different packing materials with Monoethanolamine (MEA) solvent in order to optimize the system. It was found that the lowest re-boiler duty of 3,444 kJ/KgCO_2 yield the highest rich CO_2 loading of 0.475 (mole CO_2/mole MEA) by using the BX type of structured packing having the highest surface area. The surface area of the different packing materials were inversely proportional to the temperature profiles along the column. Furthermore, the packing materials with higher surface areas yielded higher CO_2 loading profiles and vice versa. The findings of this study and recommendation would help further research on optimization of solvent-based CO_2 capturing technologies.

1. Introduction

The increasing population, industrialization, urbanization, and energy consumption is causing huge environmental pollution worldwide (Nizami et al., 2017). The gradual increase in the atmospheric concentration of greenhouse gases (GHG) such as CO_2, CH_4, nitrous oxides (NO_x) and chlorofluorocarbons (CFCs) is one of the most concerning environmental issue for causing climate change (Abu-Zahra et al., 2007). Among these gases, CO_2 alone is accountable for around 50 % of this increase as evaluated by the intergovernmental panel on climate (IPCC) (IPCC, 2005). The combustion of fossil fuels like oil and gas in power plants is the main source of CO_2. Many countries are striving to shift the energy generation from fossil fuels to renewable and other non-fossil fuel sources, but the overall progress is relatively slow (Ouda et al., 2016). In order to achieve a significant reduction in CO_2, it is critical to continue improving the power plants efficiencies, reducing energy consumption, adopt alternative energy generation processes (Rehan et al., 2018), and combined with CO_2 capture and storage (CCS) technologies for the long term.

The captured CO_2 could be utilized in petrochemical and food industries. It can also be stored underground to prevent its release into the environment (Abu-Zahra et al., 2007). Adsorption, absorption, membranes, physical and biological separation techniques are used to separate the CO_2 from exhaust gases. The most widely used systems, for combustion-based power plants, are amine-based CO_2 absorption method that works for dilute systems with low CO_2 concentrations. This technique is available commercially, user-friendly and could be fitted to current power plants. The absorption method uses solvents that have a strong affinity for CO_2. These solvents can be regenerated at higher temperatures, requiring heat energy for the regeneration process. One of the most commonly used solvents is monoethanolamine (MEA). An extensive research is underway to improve the efficiencies of these solvent-based CO_2 capturing systems using various process simulation techniques (Abu-Zahra et al., 2007). Modelling of CO_2-MEA stripping system were conducted using NRTL model while the Henry's law and RSK Equation of State were employed to describe CO_2 solubility and vapour properties, respectively (Madeddu et al., 2017), however they did not include whole amine circulation loop in the study. This study is a follow-up of the previous study made by Rehan et al. (2017) who investigated energy savings in post-carbon capture through intercooling mechanism using Aspen Hysys.

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The study aimed to optimize the solvent based CO_2 absorption system. ASPEN Plus software package was used for process modeling of CO_2 absorption based on aqueous MEA solution. A model was developed for the absorber and the stripper columns in order to analyze the effect of the different types of random and structured packing materials on the CO_2 absorption process. The effect of packing structures on re-boiler duty, liquid phase temperature profiles and CO_2 loading profiles were studied.

2. Methodology

2.1 Experimental design

ASPEN Plus (ver.8) was used to model and optimize the process of CO_2 capturing using MEA solvent. It was used to develop the comprehensive flow sheet with the applicable mass and heat transfer correlations as well as the liquid hold up. ASPEN Plus was used due to its ability to handle a wide variety of packing types which include different sizes and materials from various vendors. In databanks, it keeps records of the packing factors for the various sizes and materials. The primary aim of any packing material is to boost the efficiency for a given capacity, at a sensible cost. To accomplish this, packing materials are designed such to get the accompanying qualities including; i) the surface area must be uniformly spread in order to enhance the vapour-liquid contact area, hence the efficiency, ii) the void space per unit volume of the column must be boosted up in order to minimize the resistance to gas flow up, upgrading the capacity of the packing, iii) the cost must be minimised. The two most critical variables for choosing packing material are surface area and void friction. For both random and structured packing used in this study, ASPEN Plus underwent a liquid hold up calculations for the gas absorption. In these calculations, it used the stichlmair correlation, which entails packing void fraction, surface area and the three stichlmair correlation constants (C1, C2, C3) (Stichlmair, 1989). These constants vary with the packing used.

2.2 Process model development

The equation of state used in this study was the NRTL. An equation of state is a PVT relation that is used to predict the thermodynamic properties of the components. The compositions of the flue gas and solvent used were extracted from literature and also provided by PACT gas turbine (under UK Carbon Capture & Storage Research Centre) included; flue gas (flow rate: 600 kg/s, 40 °C, 1 bar), flue gas composition (CO_2: 4.5 %, N_2: 77.5 %), O_2: 18 %), MEA solvent (30 wt.%, 300 mbar, 40 °C). The recommended specifications selected and used in the rate-based model of the CO_2 capture process are shown in Table 1. These parameters were used in the model development to simulate the absorber and stripper. The unit operation block chosen for the absorber and the stripper was the Rad-frac model (Arachchige and Melaaen, 2012). MEA was used as a solvent in the simulation of the process model. NRTL equation of state was used for the model development in ASPEN Plus (2006). The specifications that will change in the simulation is the packing types, and the significant packing factors based on the packing material changed. The flue gas and the solvent conditions were kept constant throughout the simulation. The flow sheet generated from ASPEN plus is shown in Figure 1.

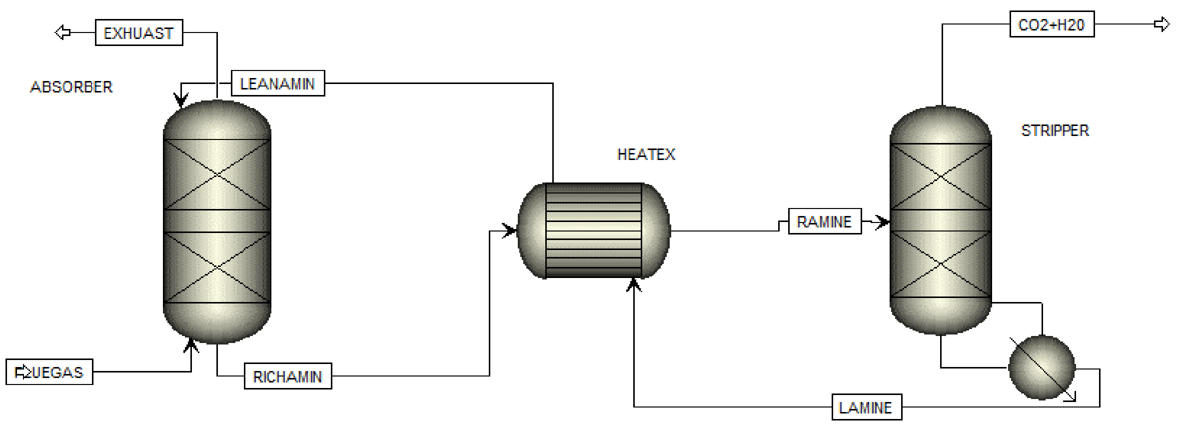


Figure 1: Flow sheet generated by ASPEN plus

2.3 Packing material and structure

Table 2 illustrates the different type of packing materials used and their relevant specification such as void percentage, surface area, size of each packing material and the three constants (C1, C2, and C3) values for each of the different packing material on the CO_2 capture process. The packing diameter and the height of each packing were kept constant for all the simulation since the simulation was performed to analyze the effect of the different types of packing materials. Mellapak-350Y, BX, and Flexipak were selected for the structured packing category and Pall rings-16, Pall rings-25 and IMTP were chosen for the random packing section. In order to check the model performance of the absorber on the effect of the packing materials, CO_2 loading profiles and the temperature profiles in the absorption column were analyzed.

Table 1: Column parameters used in the absorber and stripper (Arachchige et al., 2012)

Parameters	Absorber	Stripper
Operating pressure (bar)	1	1.5
Temperature (°C)	40	40
Number of stages	12	6
Pressure drop (bar)	0.1	0.1
Condenser	None	Partial vapor
Re-boiler	Kettle	Kettle
The height of packing (m)	25	20
Type of packing	Pall rings, IMTP, Flexipak, Mellapak, and BX.	Pall rings, IMTP, Flexipak, Mellapak, and BX.
The diameter of packing (m)	19	15
Interfacial area factor	1.2	1.5
Thermodynamic model	NRTL	NRTL

Table 2: Packing materials parameters (Arachchige and Melaaen, 2012).

Packing type	Packing size (mm)	Surface area (m^2/m^3)	Voids $_\varepsilon$(%)	C_1	C_2	C_3
Structured Packing						
BX	-	450	86	15	2	0.35
Flexipac	250Y	250	99	0.866	-0.088	0.6980
Mellapak	250Y	250	98	1	1.0	0.3200
Random Packing						
Pall rings	16	341	93	0.050	1.0	3.0
Pall rings	25	205	94	0.050	1.0	3.0
IMTP	25	207	97	0.815	-0.106	1.499

3. Results and discussion

3.1 Effect of packing structure on re-boiler duty

The effect of various structure on CO_2 capture efficiency in absorption column has been analyzed. The re-boiler duty was calculated for each of the different packing structure used as shown in Table 3. The results showed that the re-boiler duty is inversely proportional to the rich CO_2 loading (mole CO_2/mole MEA) in regard to the surface area of the individual packing material. For example, the highest re-boiler duty of 3,865 kJ/KgCO_2 yields the lowest rich CO_2 loading of 0.455 (mole CO_2/mole MEA). This highest re-boiler duty was obtained for the pall rings type of random packing structure. Similarly, the lowest re-boiler duty of 3,444 kJ/(Kg CO_2) yields the highest rich CO_2 loading of 0.475 (mole CO_2/mole MEA).

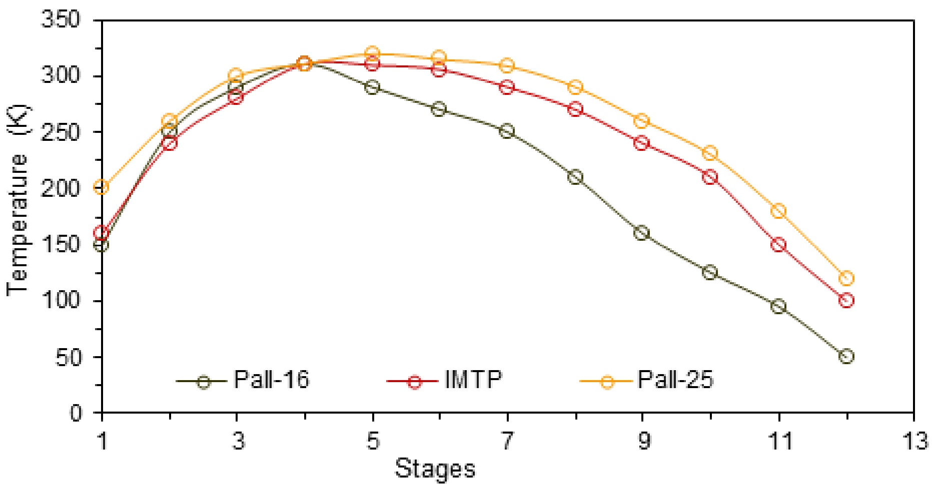
This was obtained when the BX type of structured packing was used. This is because BX has the highest surface area and therefore the rich CO_2 loading is much higher in the absorption column and the needed solvent circulating will be lower. Hence, there is a reduction in the amount of solvent process in the stripper, which would obviously require less amount of energy to heat up the solvent.

Table 3: Re-boiler duty and Rich CO_2 loading of the different types of packing

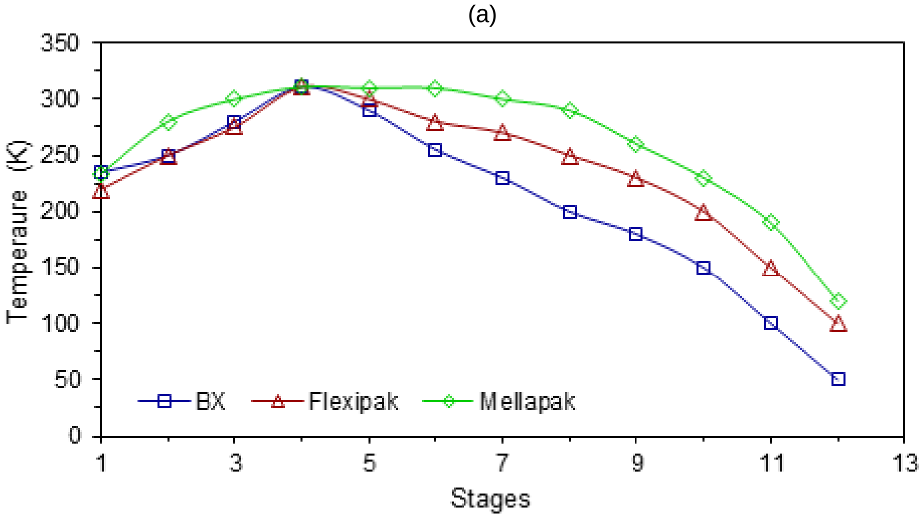
Parameters	Structured Packing			Random Packing		
	BX	Flexipac	Mellapak	Pall rings	Pall rings	IMTP
Size (mm)	-	250Y	350Y	16	25	25
Re-boiler duty (kJ/KgCO_2)	3,444	3,543	3,512	3,610	3,865	3,765
Rich CO_2 loading (mole CO_2/mole MEA)	0.475	0.470	0.471	0.465	0.455	0.458

3.2 Effect of packing structure on temperature profiles

Figure 2 (a) shows the temperature profiles for the random packing materials (IMTP, Pall-16 and Pall-25 ring). Pall-16 has the lowest temperature profile among the random packing materials. This is because it has the highest surface area as compared to other random packing types. This means that the surface area of the different packing material is inversely proportional to the temperature profiles along the column. A decrease in the surface area of the packing material increases the temperature profile and vice versa. The temperature profiles of the structured packing are like the random packing profiles. In the structured packing, BX packing material has the highest surface area (Table 2) and the lowest temperature profile as shown in Figure 2(b). Whereas, mellapak packing structure yield the highest temperature profile due to its lower surface area comparatively.



(a)



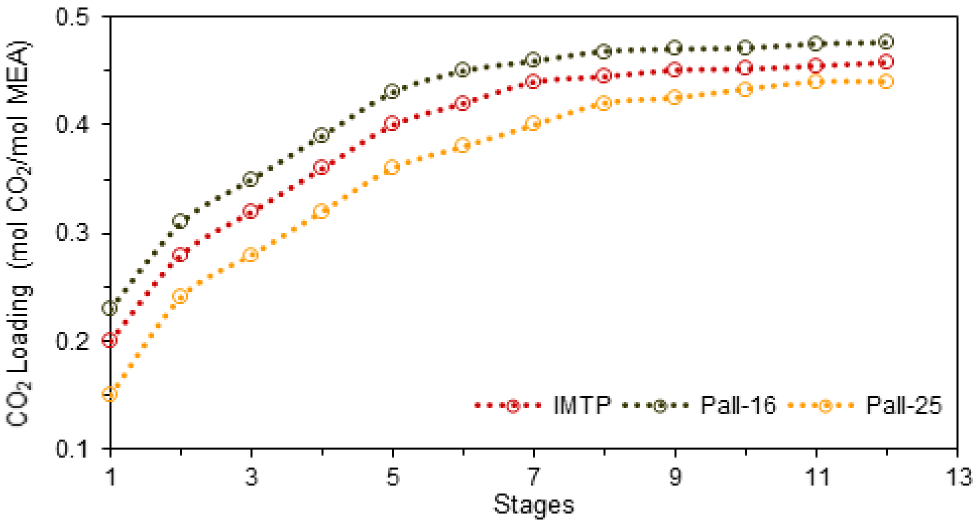
(b)

Figure 2: Comparison of liquid phase temperature profiles for (a) random packing, and (b) structured packing.

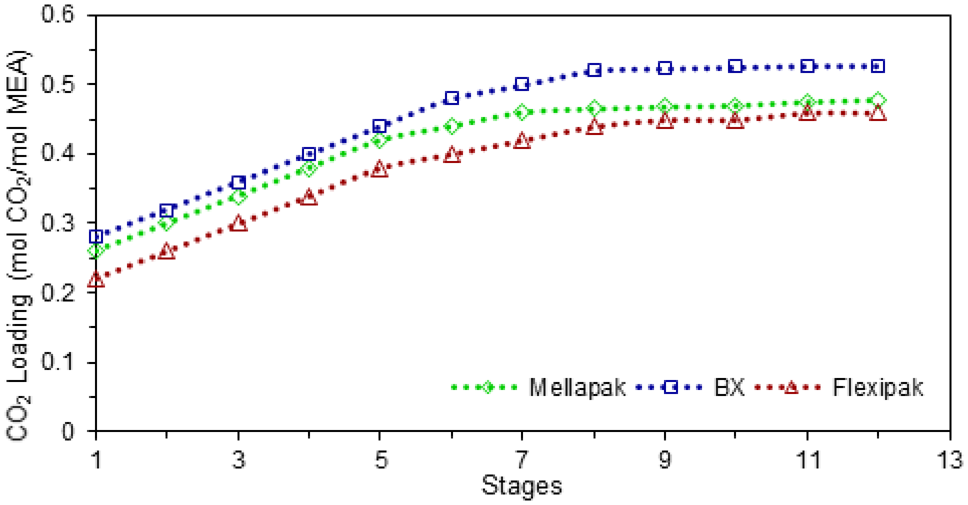
The temperature profiles exhibit a temperature bulge at the top of the column. The bulge in temperature occurs due to the very high exothermic reactions occurring at the top of the column. From the temperature profiles graphs, the maximum temperature reached is 311 K for both random and structured packing materials. This analysis is important because the rich CO_2 loading is greater when the surface area is higher and therefore high quantity of CO_2 can be absorbed by using a little amount of the solvent. Hence, the total quantity of the solvent moving inside the absorber column is reduced which lowers the internal temperature of the column.

3.3 Effect of packing structure on CO_2 loading

As stated earlier, the CO_2 loading profiles are analyzed to investigate the effect the different types of packing on CO_2 loading. Figure 3 (a) and (b) show the CO_2 loading profiles along the absorber column for both random packing and structured packing. The random structures pall rings-16, IMTP and pall rings-25 yield the CO_2 loading profiles in the order of highest to lowest (Figure 3a). In comparison, the highest to lowest yields of CO_2 loading profiles were obtained from structured packing types BX, mellapak, and flexipak respectively (Figure 3b). Both the highest yields of CO_2 loading profiles from pall rings-16 and BX were due to their higher surface area. Hence the amount of the CO_2 that can be absorbed by the solvent stream was higher. This shows that packing materials with higher surface area yield a higher rich CO_2 loading.



(a)



(b)

Figure 3: Comparison of CO_2 loading profiles for (a) random packing, and (b) structured packing

4. Conclusions

The effect of various random and structured packing materials on CO_2 capturing system has been studied. Aspen plus was used to develop the CO_2 capture model for different packing materials with Monoethanolamine (MEA) solvent in order to optimize the system. Re-boiler duty, rich CO_2, and temperature profiles are very vital parameters when selecting a packing material for CO_2 absorption column. BX structured packing material was found to be the best material, as it showed the lowest re-boiler duty of 3,444 kJ/KgCO_2 with the highest rich CO_2 loading of 0.475 (mole CO_2/mole MEA), due to its highest surface area. It is recommended to do further research on the effect of the packing structures by using a different type of solvents such as NaOH in order to develop the optimized CO_2 capturing system.

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