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Application of rotating packed bed technology for biogas upgrading

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Abstract. Biogas is a renewable energy source consisting mainly of methane, carbon dioxide, and other impurities. A purification process is required to remove the impurities (biogas upgrading and purification) to meet the requirements as an energy source for vehicles. Removal of CO_2 from the biogas stream, which accounts for about 40% of the impurities, is necessary to produce biogas (mainly methane) for use in vehicles. Chemical absorption of CO_2 using a rotating packed bed was considered due to its high CO_2 absorption efficiency and small column size. Aspen Plus and Visual Fortran software were used to develop the model, and monoethanolamine (MEA) was used as the absorbent. The developed model was validated with experimental data, where the relative error is less than 10%. The process analysis performed shows: (a) biogas purity increases with rotation speed. (b) An increase in lean solvent concentration leads to an increase in CO_2 capture efficiency and biomethane purity. (c) An increase in biogas throughput leads to an increase in biogas purity. The study may be useful for the design and operation of intensified CO_2 capture from biogas streams for vehicle applications.

1 Introduction

The consumption of fossil fuels has a significant impact on the surrounding natural environment. The mining, processing, and use of fossil fuels all have the potential to contaminate important natural resources such as water [1]. In addition, the combustion of fossil fuels results in the emission of hazardous compounds into the atmosphere, which contributes to the worsening of air pollution and has a negative impact on air quality at the local, regional, and global scales [2]. Combustion of fossil fuels results in the emission of greenhouse gases, notably carbon dioxide, which has a key influence in both the phenomena of global warming and the consequent changes in climatic patterns [3]. There is some debate about whether or not fossil fuels can be used sustainably over the long term because of the finite nature of these fuels and the potential difficulties that are associated [4]. The utilization of sources of energy that are renewable is absolutely necessary for the long-term sustainable preservation of the planet [5].

Biogas is a renewable energy source of methane that can be used for vehicles but this needs to be purified to remove the contaminations. Impurities such as hydrogen sulfide, carbon monoxide, siloxanes, and carbon dioxide can be removed from biogas using several

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biogas upgrading technologies that have been developed in recent years. Investigations into upgrading biogas have been conducted using a wide variety of physical, chemical, and biological processes. The physical and chemical approaches, such as water scrubbing, physical absorption, and pressure swing adsorption, are almost as effective as the optimal solution, but they still demand a considerable amount of energy and resources [6]. Biological approaches have received less research, although there is reason to be optimistic about their potential [7]. The methods of pressure swing adsorption, high-pressure water scouring, membrane separation, and cryogenic separation are all examples of biogas upgrading technologies that are currently available for commercial use [8]. The environmental performance of biogas upgrading routes can be improved by the exploitation of renewable electricity, the decrease of methane leakage, the utilization of biogenic CO_2 sources, and the limitation of the use of nitrogen fertilizer [9]. The transformation of biogas into biomethane has the potential to reduce greenhouse gas emissions in the transportation sector while also enhancing energy independence. Despite the fact that recent developments in biogas upgrading technologies have showed considerable prospective advantages over traditional methods, additional research and development is still required to develop solutions that are economically, ecologically, and socially sustainable.

According to the findings of a number of researchers, shows that process intensification using rotating packed bed technology has the potential to cut down both capital and operational expenses [10–13]. Studies by Joel et al. [12,14] demonstrated that there is a considerable reduction in size of around 12 times for the absorber and 9.63 times for the stripper when compared to conventional columns for CO_2 capture. In this study, a rotating packed bed absorber model was developed for biogas upgrading using MEA solvent. Process analysis was done on the effect of rotor speed, MEA concentration and solvent to biogas ratio on biogas purity performance.

2 Model development

Currently, there is no readily available model for an RPB absorber in any of the publicly accessible model libraries. To facilitate the simulation of an intensified absorber using the rate-based model in Aspen Plus®, existing mass/heat transfer correlations which were affected by centrifugal force were replaced with customized subroutines coded using Intel® Visual FORTRAN.

In our study, we considered several correlations, including the liquid-phase mass transfer coefficient proposed by Chen et al. [15], the gas-phase mass transfer coefficient suggested by Chen [16], the estimated interfacial correlation provided by Luo et al [17], and the liquid-hold-up correlation presented by Burns et al. [18]. To account for the combined effects of drag and centrifugal forces, gas-solid sliding, and radial acceleration, we incorporated the dry pressure drop expression proposed by Llerena-Chavez & Larachi [19].

Electrolyte Non-Random Two-Liquid (ElecNRTL) Activity Coefficient Model in the Aspen Plus® software was used for calculation of the vapor-liquid equilibrium, chemical equilibrium, and physical properties of the system. Standard change in Gibbs free energy was used to calculate equilibrium constants assuming that the equilibrium reactions occur within the liquid layer.

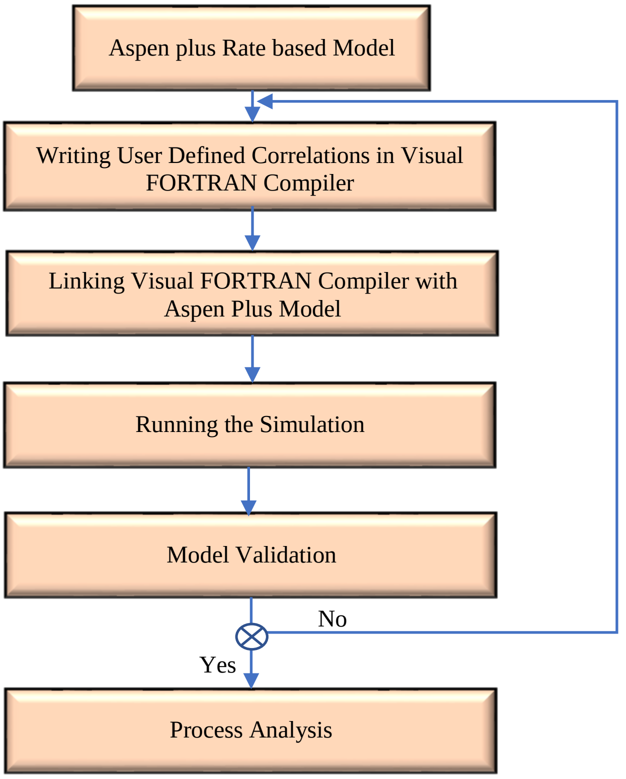

Fig. 1 Modelling implimentation procedure [11].

3 Results and discussion

3.1 Model validation

The developed model needs to be validated to have confidence on the simulated results. Because there is no experimental data available for rotating packed bed absorber use for biogas upgrading. The model was validated based on available data for CO_2 capture using rotating packed bed reported in Jassim et al. [20]. The output parameters considered for the validation are CO_2 capture efficiency and rich solvent loading. Figure 2a showed the result of model validation based on CO_2 capture efficiency, it was observed that the model predicted experimental results very well with percentage error of 10%. Since rich loading is an output parameter from the model and the experiment, Figure 2b shows that rich loading was predicted by the model with percentage error of less than 10%. After that, the predicted model was then used to purify the biogas to a grade that would be appropriate for use in automotive applications by employing MEA solvent as the absorbent. The process conditions that were used in the modelling studies are listed in Table 1.

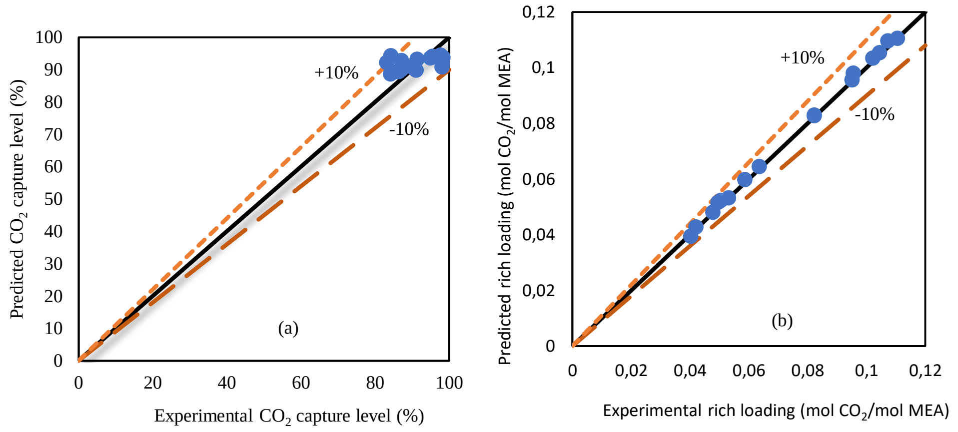

Fig. 2. Parity plot on (a) CO_2 capture efficiency (b) rich loading.

Table 1. Biogas input conditions.

Variables	Values
Temperature (℃)	40
Pressure (atm)	1
Biogas composition (wt%)	
CH_4	65
CO_2	31
H_2O	2
H_2S	0.15
N_2	0.5

3.1.1 Effect of rotor speed on biomethane purity and CO_2 removal efficiency

The amount of energy that is required, particularly for the rotation of the bed, is a critical parameter that needs to be decreased in order to achieve optimal biogas purity while simultaneously reducing the amount of energy that is required. It is essential to do research on the effect that rotor speed has on the purity of biomethane and the effectiveness of CO_2 removal. According to Figure 3, both the efficiency of CO_2 removal and the purity of the biomethane produced increase as the rotor speed rises. This is due to the fact that at increased centrifugal acceleration, more combined droplet and film flow is predominant in an RPB absorber, which ultimately leads to enhanced mass transfer flux. In addition, Burns and Ramshaw [21] found that when the rotor speed was increased, the issue of liquid mal-distribution will decrease, which resulted in a higher wetted surface. This, in turn, contributed to an improvement in the rate at which mass was transferred. A study that is very similar to this one was published in by Joel et al. [12] for CO_2 capture from power plants utilizing rotating packed bed technology.

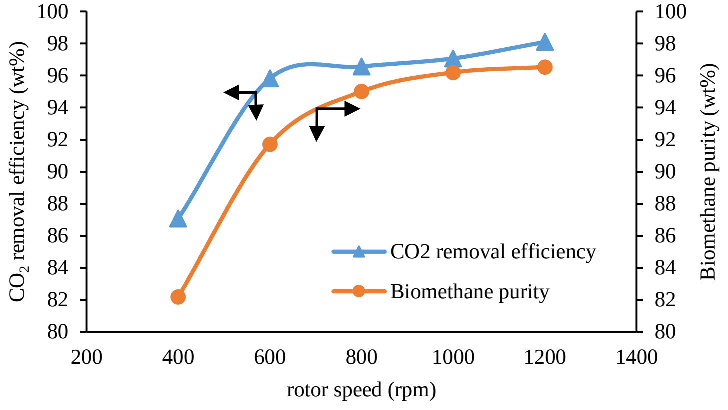

Fig. 3. Effect of rotor speed on CO_2 removal efficiency and biomethane purity (Conditions : 55 wt% MEA concentration; 400 – 1200 rpm motor speed; solvent to biogas ratio = 7.5 kg/kg).

3.1.2 Effect of MEA Concentration on biomethane purity and CO_2 removal efficiency

Concentration of MEA in the absorbent will play a significant role in the selection of material of construction of the rotating packed bed absorber. This is because at higher concentration, it is expected that the corrosion tendency of the RPB will increase which might to the need of highly corrosion resistance material that are generally expensive. Therefore, study on the effect of concentration on the biomethane purity and CO_2 capture efficiency is shown in Figure 4. It was observed that as the MEA concentration increases the biomethane purity and CO_2 removal efficiency increases. As reported in Freguia and Rochelle [22] the reaction between CO_2 and MEA is first order reaction and is a function of concentration.

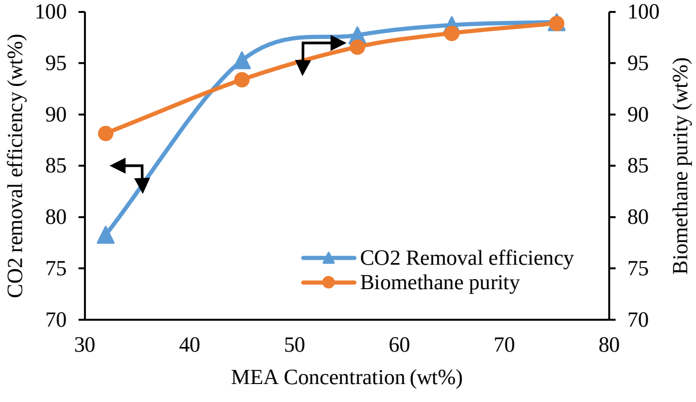

Fig. 4. Effect of MEA concentration on CO_2 removal efficiency and biomethane purity (Conditions: MEA concentration = 32 - 75 wt% ; motor speed = 400 – 1200 rpm; solvent to biogas ratio = 7.5 kg/kg).

3.1.3 Effect of solvent to biogas ratio on biomethane purity and CO_2 removal efficiency

The influence of solvent to biogas ratio on the amount of CO_2 that is removed and the purity of the biomethane is shown in Figure 5. It was discovered that the ratio of solvent to biogas has an effect on the purity of the biomethane produced. This is because a higher ratio of solvent to biogas results in a higher rate of CO_2 removal. Also, higher ratio of solvent to biogas results in a higher absorbent flowrate, which in turn results in a higher amount of solvent being dispersed throughout the packing, which results in a high amount of liquid per unit volume. Because of this, a higher ratio of solvent to biogas results in a greater gas-liquid contact area. This study is crucial because a larger ratio of solvent to biogas will result in a bigger volume of solvent recirculation, which in turn will result in a higher amount of duty for the reboiler. As a result, it is essential to maintain as low of a ratio of solvent to biogas as is practically practicable in order to meet the requirements for reduced operational costs associated with solvent regeneration.

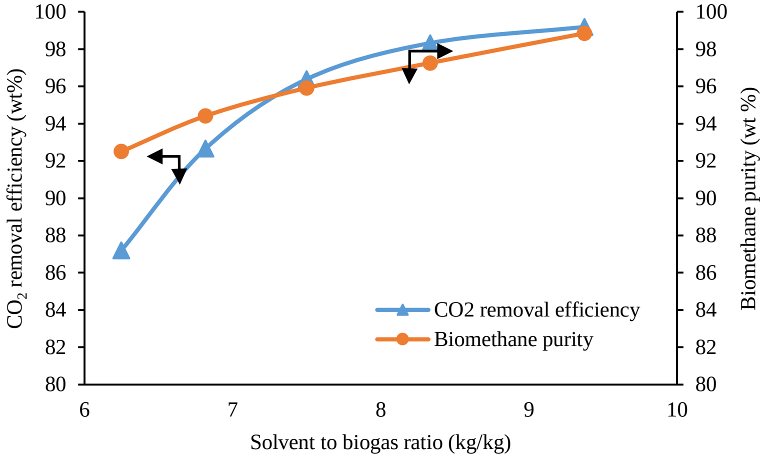

Fig. 5. Effect of solvent to biogas ratio on CO_2 removel efficiency and biomethane purity (conditions : MEA concentration = 55 wt% ; motor speed = 1000 rpm ; solvent to biogas ratio = 6.25 – 9.37 kg/kg).

4 Conclusion

The Aspen Plus and Intel Visual Fortran modelling environments were utilized in the biogas upgrading model development. The model was validated using experimental data, and the percentage error on capture efficiency as well as rich loading was less than 10% in both cases. Process studies were performed on the effect of rotational speed on the purity of biomethane and the efficiency with which it was captured. The results of the study indicate that the biomethane purity and CO_2 removal efficiency both improve with increasing rotor speed. There is a positive association between the effect of MEA content and the ratio of solvent to biogas in terms of biomethane purity and CO_2 capture efficiency. In conclusion, the research demonstrates the possibility of utilizing solvents for CO_2 removal in order to improve the purity of biogas so that it can be used in vehicles.

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