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Research Article

CO_2 Absorption Through Super-hydrophobic Hollow Fiber Membrane Contactors

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Abstract

This study aims to evaluate the performance of super hydrophobic hollow fiber membrane contactors to absorb CO_2 using water and diethanolamine (DEA) solution as absorbents. During the experiment the absorbents flowed through lumen fibers while the CO_2 flowed through the shell side of the membrane contactor. Absorbents flow rates as well as the number of fibers in the contactor are the variables observed in this study to see their effects on the overall mass transfer coefficient and flux as well as the absorption efficiency in the membrane contactor. The experimental results show that the overall mass transfer coefficient and the flux increased with increasing the absorbents flow rate. The number of fibers in the contactor have different effects on the overall mass transfer coefficient and the flux for both absorbents. The mass transfer coefficient and the flux increased for water absorbent and decreased for DEA solution. Meanwhile, the CO_2 absorption efficiency increased with increasing the water flow rate and the number of fibers in the membrane contactor due to the increase in the turbulence and the contact area, respectively.

Key words: Flux, mass transfer coefficient, membrane contactor, super-hydrophobic

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Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Combustion of fossil fuels in power plants and motor vehicles in the world is the biggest contributor to CO_2 emissions that affect climate change. In addition, the presence of CO_2 in natural gas also poses problems in its operation and the economics. Carbon Capture and Storage (CCS) can be used for mitigating CO_2 emissions from fossil fuel combustion and natural gas industry, where membrane gas-solvent contactors have been applied as a hybrid approch (Favre and Svendsen, 2012). The CO_2 absorption through the membrane contactor is generally focused on the use of porous membranes, which are suffered if the membrane pores are wetted by the solvent (Yu *et al*., 2015). The wetting of membrane pores significantly affected the mass transfer coefficients as the resistance of membrane phase increasing (Keshavarz *et al*., 2008; Lu *et al*., 2008). It was reported that the membrane wetting can cause a significant drop of CO_2 flux for both physical and chemical absorptions up to 90% when water used as the absorbent (Zhang *et al*., 2008). Therefore, the selection of the liquid absorbents is an important measures to prevent the wetting of the membrane (Rongwong *et al*., 2009). In addition, the high temperature of absorbent can reuduce the mass transfer coefficient in the membrane contactor (Yan *et al*., 2007).

The other important element of the membrane contactor is membrane material, which should have important properties such as high hydrophobicity, high surface porosity, low mass transfer resistance as well as resistance to various chemical liquids (Mansourizadeh, 2012). The high hydrophobicity property is needed to prevent the wetting of membrane pores that can increase the overall mass transfer coeffcient and therefore, the choice of membrane material is critical to the efficiency of the process (Goyal *et al*., 2015). This study aims to evaluate the performance of super hydrophobic hollow fiber membrane contactor to absorb CO_2 using water and diethanolamine (DEA) solution as absorbents. The flow rates of absorbents as well as the number of fibers in the membrane contactor will be observed to see their effects on CO_2 absorption processes in the contactor.

MATERIALS AND METHODS

Figure 1 shows the schematic diagram of CO_2 absorption using a membrane contactor, which has already reported (Yu *et al*., 2015). The super-hydrophobic hollow fiber membrane contactors used were supplied by PT GDP Filter Bandung. The CO_2 gas (99%) and DEA were purchased from BOC Gases and Merck, respectively. The super-hydrophobic fiber membrane used is polypropylene-based with outer and inner diameter of about 525 and 235 µm, respectively. Hollow fiber membrane contactors used were 7.6 and 25 cm in diameter and length, respectively, which consist of 2000, 4000 and 6000 fibers. During the experiment the absorbents, water or DEA solution (5% vol in water) flowed through the lumen side of the membrane fiber while CO_2 gas flowed through the shell side of the membrane contactor. The absorbents flow rate was measured using liquid flow meter Krohne, whilst inlet and outlet gas flow rate was measured using mass flow meter Sierra Top Trak Instruments.

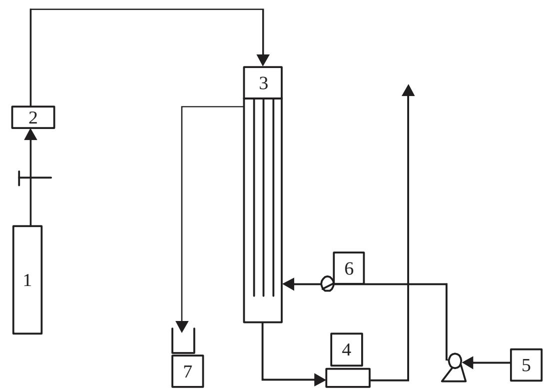

Fig. 1: Schematic diagram of experimental set up: (1) Feed gas, (2) Mass flow meter, (3) Super-hydrophobic hollow fiber membrane contactor, (4) Mass flow meter, (5) Absorbent reservoir, (6) Flow meter and (7) Absorbent reservoir

The overall mass transfer coefficient, K_{OVL}, based on experiment is calculated by Eq. 1 of Wang *et al*. (2004a):

$$K_{OVL} = \left(Q_{Gin} / A_m \right) \ln \left(C_{in} / C_{out} \right) \quad (1)$$

where, Q_{Gin}, A_m, C_{in} and C_{out} are inlet gas flow rate, membrane area and inlet and outlet CO_2 concentration, respectively. Meanwhile, flux, J and absorption efficiency, %R, were calculated by Eq. 2 and 3:

$$J = \left(Q_{Gin} - Q_{Gout} \right) * RT / Am \quad (2)$$

$$R(\%) = 100 \left(Q_{Gin} - Q_{Gout} \right) / Q_{Gin} \quad (3)$$

where, Q_{Gout}, R and T are the flow rate of outlet CO_2, gas constant and temperature, respectively.

RESULTS AND DISCUSSION

The CO_2 transfer mechanism through the membrane contactor can be explained as follows: first, the CO_2 in the gas phase in the shell side of the membrane contactor will diffuse into the surface of the membrane fibers; then the CO_2 gas in the surface of the membrane fibers will diffuse through the pores of the membrane fiber to the surface of the membrane fibers containing absorbents and finally, the CO_2 gas that is in contact with the absorbents is absorbed by the absorbents. There are three mass transfer resistances in the process of CO_2 absorption by the absorbents in the hollow fiber membrane contactors, namely; mass transfer resistance in the gas phase in the shell side of the membrane contactors, mass transfer resistance in the pores of the membrane fiber and mass transfer resistance in the absorbents phase in the lumen fibers. Therefore, the equation of mass transfer coefficient in the membrane contactors can be written as in Eq. 4 (Wu and Chen, 2000):

$$\frac{1}{K_{OV}} = \frac{H}{k_G} + \frac{H}{K_m} + \frac{1}{k_L} \quad (4)$$

where, K_{OV}, k_G, k_m, k_L and H are overall mass transfer coefficient, mass transfer coefficient in gas, membrane and liquid phases and Henry's constant, respectively.

Mass transfer resistance in gas phase can be ignored as the gas used in the experiments is pure CO_2 so that there is no competitor for CO_2 to reach the fiber membrane surface in outer side. The mass transfer resistance in the membrane phase can also be ignored as the membrane pores are hydrophobic and gas filled so that the CO_2 diffusivity is much higher than in a liquid phase (Scholes *et al*., 2015). Therefore, in the CO_2 absorbents system in the super hydrophobic hollow fiber membrane contactor, the overall mass transfer coefficient is only affected by mass transfer resistance in liquid phase and Eq. 4 can be simplified in Eq. 5 as:

$$\frac{1}{K_{OV}} = \frac{1}{k_L} \quad (5)$$

The effects of the absorbent flow rate and the number of fiber in the membran contactor on the amount of CO_2 absorbed by the absorbents is shown in Fig. 2. The amount of CO_2 absorbed by the absorbents increases with the increase in the absorbent flow rate due to increasing the turbulence in the liquid boundary layer (Wang *et al*., 2004a) and increases with the increase in the number of fiber in the contactor due to increasing the surface area for contact.

The effects of the absorbent flow rate and the number of fiber in the membran contactor on the overall mass transfer coefficients is shown in Fig. 3. Figure 3 reveals that the mass transfer coefficient increases with increasing in absorbents flow rate in the lumen fiber in the membrane contactor. The controlling resistance for the mass transfer in hollow fiber membrane contactor is usually dominated in the liquid phase (Wang *et al*., 2004b). An increase in the absorbents flow rate will increase the turbulence in the liquid boundary layer and

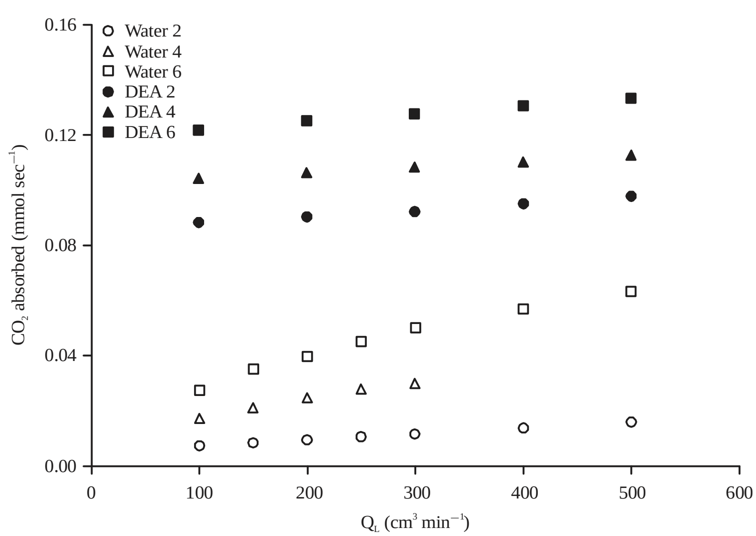

Fig. 2: Effect of water flow rate, Q_L, on the amount of CO_2 absorbed on the membrane contactor consists of 2000, 4000 and 6000 fibers and CO_2 flow rates of 320 $cm^3\ min^{-1}$

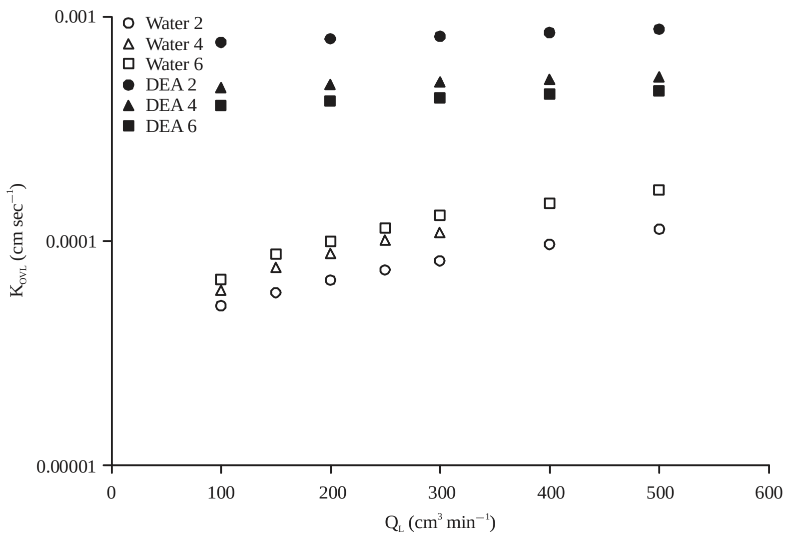

Fig. 3: Effect of water flow rate, Q_L, on the overall mass transfer coefficient, K_{OV}, on the membrane contactor consists of 2000, 4000 and 6000 fibers and CO_2 flow rates of 320 $cm^3\ min^{-1}$

will reduce the mass transfer resistance in the liquid phase. The overall mass transfer coefficient will increase as well (Dindore *et al*., 2004; Franco *et al*., 2008). Furthermore, increasing the absorbents flow rate will increase the surface renewal effects that will increase the overall mass transfer coefficient (Wu and Chen, 2000). The increasing in the mass transfer coefficient with the absorbents flow rates also indicated that the membrane was not wetted by the absorbants (Wang *et al*., 2004a).

The number of fibers in the contactor have a difference effect for both absorbents on the overall mass transfer coefficient at the same liquid flow rate. The increase in the number of fibers in the contactor will reduce the absorbent flow rate in the individual fiber at the same overall absorbent flow rate, which lead to the reduce of the overall mass transfer coefficient (Mansourizadeh and Ismail, 2009). On the other hand, the increase in the number of fibers in the contactor will increase the contact area for the mass transfer, which lead to the increase in the overall mass transfer coefficient. Figure 3 shows that the overall mass transfer coefficient for the water absorbent increases with increasing the number of fibers in the contactor at the same absorbent flow rate, indicating that the effect of the surface area for contact more dominant than the effect of the absorbent flow rate. Meanwhile, the overall mass transfer coefficient for the DEA solution decreases with increasing the number of fibers in the contactor at the same absorbent flow rate, indicating that the effect of the absorbent flow rate more dominant than the effect of the surface area for contact.

As with the mass transfer coefficient, the flux of CO_2 through the membrane fibers increases with increasing the absorbent flow rate in the membrane contactor due to the turbulence and surface renewal effects (Dindore *et al*., 2004; Franco *et al*., 2008; Wu and Chen, 2000) as shown in Fig. 4. Based on Eq. 2, the flux increases with increasing the amount of CO_2 absorbed and decrease with increasing the surface area for contact. Based on Fig. 2, the amount of CO_2 absorbed increases with increasing the absorbent flow rate and the number of fiber in the contactor. Figure 4 shows that the flux of CO_2 through the membrane fibers for the water absorbent increases with the increase in the number of fibers in the contactor, indicating that the effect of the surface area for contact more dominant than the effect of the absorbent flow rate. Meanwhile, flux of CO_2 through the membrane fibers for DEA solution decreases with increasing the number of fibers in the contactor at the same absorbent flow rate, indicating that the effect of the absorbent flow rate more dominant than the effect of the surface area for contact.

Figure 5 shows the effect of the absorbents flow rate on the CO_2 absorption efficiency, R%, at the various numbers of fibers in the membrane contactor. Based on Eq. 3, the CO_2 absorption efficiency, R%, directly proportional to the amount of CO_2 absorbed by the absorbents. The CO_2 absorption efficiency increases with increasing the absorbents flow rate in the membrane contactor due to increasing turbulence the absorbents boundary layer (Dindore *et al*., 2004; Franco *et al*., 2008; Wang *et al*., 2004a; Wu and Chen, 2000) and also increases with the increase in the number of fibers in the membrane contactor due to more contact surface area for absorption. The facts for CO_2 absorption efficiency, R%, is

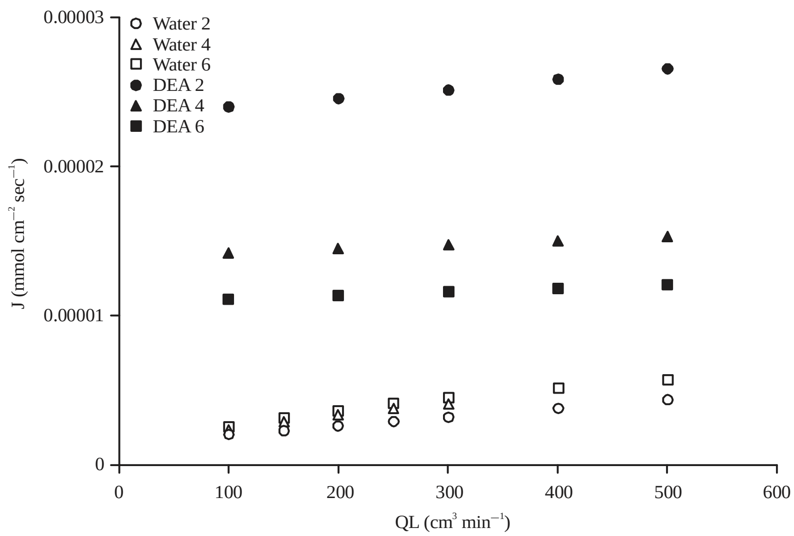

Fig. 4: Effect of water flow rate, Q_L, on the flux CO_2 through the membrane fibers, J, on the membrane contactor consists of 2000, 4000 and 6000 fibers and CO_2 flow rates of 320 cm^3 min^{-1}

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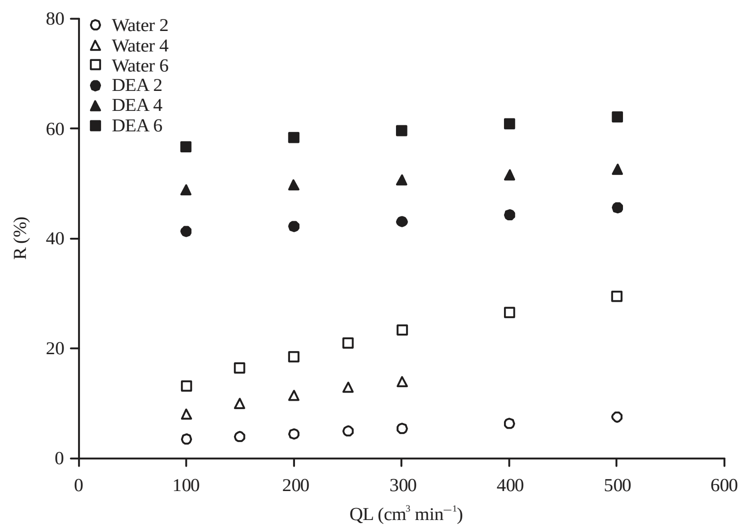

Fig. 5: Effect of water flow rate, Q_L, on the CO_2 absorption efficiency, R%, on the membrane contactor consists of 2000, 4000 and 6000 fibers and CO_2 flow rates of 320 cm^3 min^{-1}

consistent with Fig. 2, where the amount of CO_2 absorbed increases with increasing the absorbents flow rate and the number of fibers in the contactor.

CONCLUSION

In the gas-liquid contact process through hollow fiber membrane contactor, the membrane is the most important element. One of the important properties of the membrane for gas-liquid contact process is high hydrophobicity, which is is needed to prevent the wetting of membrane pores that can increase the overall mass transfer coeffcient. This study utilized polypropylene super-hydrophobic hollow fiber membrane contactor to absorb CO_2 using water and DEA solution (5% vol in water) as absorbents. In the experiments, the absorbent flowed through the lumen of fibers while the CO_2 gas flowed through the shell side of the contactor. The Experimental results showed that the mass transfer coefficients and the fluxes for both absorbents increased with increasing the absorbents flow rates. Meanwhile, the mass transfer coeffcient and the flux increased for water absorbent and decreased for DEA solution with increasing the number of fibers in the contactor. The CO_2 absorption efficiency increased with increasing the absorbents flow rates and the number of fibers in the membrane contactor.

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