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Membrane Contactors for Post-Combustion CO_2 Capture: Model Development, Sensitivity Analysis, and Application to CO_2 Capture from a Coal-fired Power Plant

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Abstract

1. Introduction

The increasing anthropogenic emission of greenhouse gases (GHGs), mainly CO_2, is the major contributor of global warming and changes in the climate system. The EU has set a long-term goal of cutting GHG emissions by 80-95% over the year 1991 level [1]. In this context, CO_2 Capture and Storage (CCS) is considered a key technology to accomplish these goals. Generally, there are three main ways to capture CO_2: post-combustion, pre-combustion and oxyfuel combustion. Among these, post-combustion CO_2 capture (PCC) is considered the most promising pathway because it can be incorporated into new and existing fossil fuel fired power plants at a relatively lower cost [2,3]. Several technologies have been suggested for CO_2 capture, including absorption, adsorption, membranes, and chemical looping [4,5]. Among those technologies, amine-based absorption of CO_2 in traditional absorbers is considered the most mature and adequate for PCC [6,7]. However, this technology has its disadvantages including large absorber size, high energy demand for solvent regeneration, and frequent operational limitations such as flooding, channeling, entrainment, and foaming [8-11].

The utilization of membrane contactors is proposed as a promising option to overcome some of these drawbacks [7,12,13]. Membrane contactor is a hybrid process that combines the principles of membrane separation and absorption processes. CO_2 is transferred from the gas-phase via a hydrophobic porous membrane to the liquid-phase where it reacts with the absorbent. The membrane contactor technology avoids some problems encountered in conventional absorbers such as flooding, channeling, entrainment, and foaming and allows independent control of the liquid and gas-phases. Membrane gas absorption offers additional advantages, such as linear scale-up, and reduction in size, with its higher surface area to volume ratio [7,13-16]. However, membrane contactors have also its disadvantages such as higher mass transfer resistance and membrane wetting [7,13-16].

2. Membrane contactor modelling

In the present work, a mathematical model has been developed based on the model from [17] to predict CO_2 absorption in Hollow fiber membrane contactor (HFMC) using MEA as a solvent (Figure 1). The model follows the 1D-2D modeling approach. Plug flow is assumed in the gas-phase while axial convection and radial dispersion are considered

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in the liquid-phase. The 1D-2D modelling approach is based on a more detailed estimation of the liquid phase concentration and temperature profiles to have a better understanding of the system. This is because the gas-phase mass transfer resistance is negligible while the effect of liquid-phase mass transfer resistance is important. As a result, the 1D model for the gas-phase decreases the complexity of the model whereas the 2D model for the liquid-phase makes the model robust.

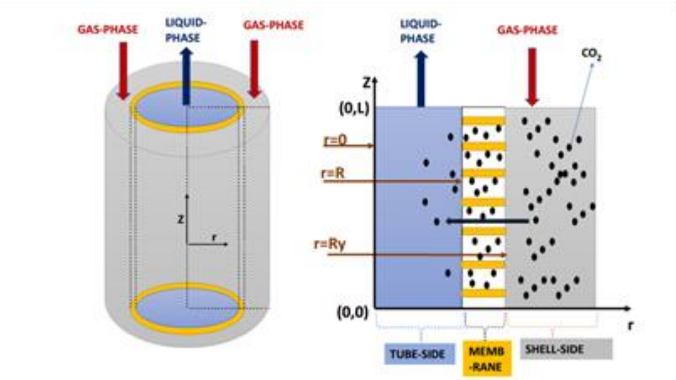

Figure 1: Illustration of the sections of the HFMC considered in the present work.

The liquid-phase is assumed to flow on the tube side while the gas-phase flows in the shell side counter currently. Several other studies [11,18,19] have followed this flow configuration. Countercurrent flow configuration is chosen since it provides a higher driving force for separation compared to the co-current flow configuration.

3. Preliminary results

First, a sensitivity study is conducted to analyze the impact of some parameters on the performance of the membrane contactor. The sensitivity study is performed to give more insight into the performance of the contactor and to facilitate the discussions. Then simulation of 90% CO_2 capture is performed by optimizing important model parameters and the requirements of the HFMC are compared with a packed column applied for the same operating conditions. Finally, concentration, temperature, and viscosity profiles of the liquid-phase are predicted and the simulation results are compared with pilot-scale experimental data from the literature.

Four parameters were studied, namely (i) the effect of gas-phase velocity, (ii) the liquid-phase velocity, (iii) the membrane fibre length, and (iv) the membrane mass transfer coefficient. Figure 2 shows the preliminary results for the sensitivity analysis.

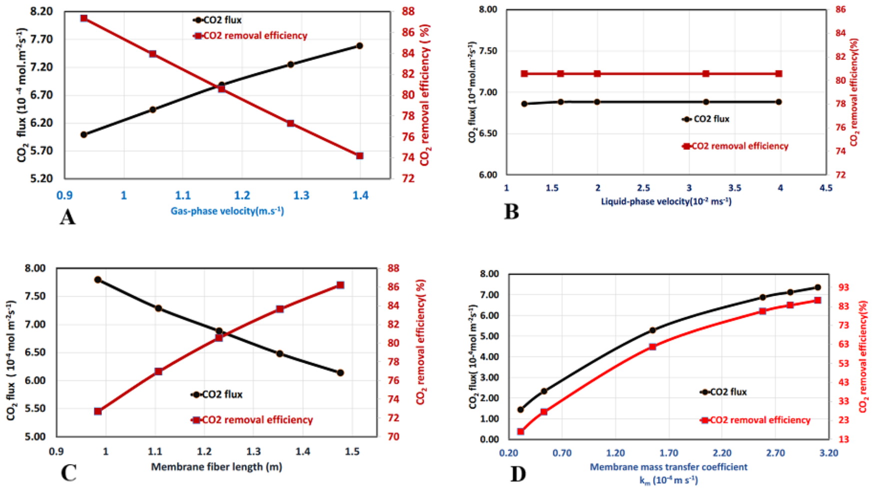

Figure 2: Effect of gas-phase velocity (A), liquid-phase velocity (B), membrane fibre length (C), membrane mass transfer

coefficient (D).

The analysis shows that CO_2 absorption flux and CO_2 removal efficiency are directly proportional to the membrane mass transfer coefficient while they are independent of the solvent lean loading and the liquid-phase velocity. Moreover, with a decrement of the gas-phase velocity and an increment of the membrane length, the CO_2 removal efficiency increases, and the CO_2 absorption flux decreases. Based on this analysis, simulation of 90% CO_2 capture from the power plant will be performed by adjusting the membrane length and the results are compared with a traditional packed column applied for the same case study. Results indicates that the absorber volume can be decreased by 86% compared to the traditional absorber, however, at the cost of several challenges such as large number of modules, size limitation, and pressure drop.

4. Conclusions

An adiabatic numerical model for CO_2 absorption in HFMC using MEA as an absorbent was developed and preliminary simulations were performed. A simulation of large-scale PCC using HFMC modules will be performed and the effect of important model parameters on the CO_2 absorption flux and CO_2 removal efficiency of the HFMC modules was studied.

The study shows that the CO_2 absorption flux increases with an increase in the gas-phase velocity and membrane mass transfer coefficient and with a decrease in membrane fibre length. Furthermore, the CO_2 removal efficiency increases with an increase in membrane mass transfer coefficient and membrane fibre length and with a decrease in gas-phase velocity. In the present work, the main mass transfer resistance resides in the membrane. Thus, the separation performance of the HFMC depends on the availability of CO_2 in the gas-phase and is independent of the liquid-phase velocity and lean loading.

The results from the simulations of the large-scale plant using the HFMC will be compared to the traditional solvent-based absorption technology in terms of equipment size and costs. Compact contactors can be explored in sectors where space is a crucial constraint, for example in the maritime sector.

Keywords: Membrane contactor; Modelling; Simulation; CO_2 capture; Chemical absorption; MEA

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