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Thin film membrane for CO_2 separation with sweeping gas method

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ABSTRACT

Different from gases separation technology using membranes and solvent, solvent-free gas separation technology is more economically and energy efficient. Due to its inherent low permeance of the membrane, the means using sweeping or vacuum are two main options to increase the mass flow rate of the fast gas (with higher selectivity) on the permeate side. This study models a typical membrane for CO_2 separation and investigates the effects of different parameters on the total mass flow rate, mass fraction of CO_2 and the mass flow rate of CO_2 in the permeate outlet. These parameters are the permeate outlet pressure, mass flow rate of mixed feeding and sweeping gases, membrane length and the height of gases zones. The results show that the mass flow rate of CO_2 in the permeate side can be enhanced dramatically by using sweeping gas method. But the mass fraction of CO_2 in permeate outlet is also significantly affected by this method. The increase of membrane length enhances both the mass fraction and mass flow rate of CO_2 in permeate outlet. But mass fraction of CO_2 on permeate outlet reaches its peak when membrane length exceeds 150 mm. The height of gases zones, however, have very limited effects on both the mass fraction and mass flow rate of CO_2 in the permeate outlet. This study provides a good guideline for designing industrial gases separation systems using membranes.

1. Introduction

Due to the ever-growing worldwide demand on energy and the combustion of fossil fuel, the tremendous amount of CO_2 emitted to the atmosphere has been criticized as the main factor of global warming. According to the data from IPCC [1], the greenhouse gases (GHG) concentrations in the atmosphere are at unprecedented levels in the last 800,000 years. Between 2000 and 2010, total GHG emissions caused by human activities increased about 10 $GtCO_2$-eq every year and 47% of the increase is contributed by energy conversion. Meanwhile, the globally averaged temperature combined land and ocean surface increased 0.85 °C between 1880 and 2012 [1]. In addition to that, up to 40% of the anthropogenic CO_2 emission is absorbed by the sea water has acidified the ocean [2,3]. If no means are adopted to reduce the CO_2 emission by human activities, this value could rise to 0.5 by the year of 2100 [4]. Because of the acidification, the dissolution of $CaCO_3$ in all water column is approximately 45–65% of the export production of $CaCO_3$ [5,6].

As an emerging technology for CO_2 capture, the membrane gas separation process has its own essential advantage. No processing costs brought by regeneration and phase change are needed because membrane technology does not require a separating agent nor it involves phase changes [7]. Meanwhile, separation of other gases and high separation efficiency can be achieved by membrane separation [8]. Besides, membrane separation technology is more space and weight efficient and is suitable for larger scale units. Hu et al. [9] studied the effects of two additives PEG (polyethylene glycol) and IM22 (PEG–PDMS copolymer, PDMS stands for Polydimethylsiloxane) on the membrane structure formation and gas pressure applied on CO_2/N_2 separation performance including CO_2 permeability and CO_2/N_2 selectivity. They found that both the PEG400 and IM22 additives to the PPE (2, 6-dimethyl-1, 4-phenylene oxide) polymer increased the porosity of the membrane and decreased the thickness of the skin layer of the membrane and hence improve the performance of the membrane gas separation considerably. As well, their results indicate that higher gas pressure enhances both the CO_2 permeability and CO_2/N_2 selectivity.

Recently, the effects of PEG and PEO-PDMS (PEO stands for polyethylene oxide) copolymer additives on the structure and performance of hollow fibers for CO_2 separation were studied by Hu et al. [10]. Similar to their previous work [9], they found out that

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PEG additives added to the dope solution which forms the membrane can modify the membrane structure and consequently enhanced the separation performance for all gases. On the other hand, PEO-PDMS can enhance the CO_2/N_2 selectivity of the hollow fiber membrane.

A new type of membrane which has high performance of CO_2 separation was developed by Scofield et al. by adding fluorinated additives to bi-block copolymers during the synthesis process [11]. The experimental results indicate that the pressure and temperature of feed gas are almost irrelevant to the CO_2/N_2 permeance. However, the higher gas temperature can have negative effects on CO_2/N_2 selectivity.

Numerically, Tahvildari et al. [12] modeled, simulated, and analyzed the economic condition of the CO_2 capture in natural gas using hollow fiber membrane with different types of flow configuration. They found that the configuration of countercurrent flow has the higher performance among the three different types of configuration. Sanders et al. [13] conducted a recent review on energy-efficient gas separation membranes for a sustainable future. The review presents the fundamental scientific principles gas separations. It was concluded that major membrane-based gas separations include hydrogen recovery, air separation, and natural gas purification. However, materials improvements and a changing industrial environment have expanded opportunities for membranes within olefin/paraffin separations, ethanol/water separations, and carbon capture applications. These separations and materials advances will continue to allow the membrane field to evolve and grow. Dai et al. [14] reviewed the recent advances in multi-layer composite membranes for gas separation. They indicated that membrane material research for gas separation has made great progress in recent decades. However, to make membrane technology more competitive in the industrial market, great efforts are needed.

As shown in the literature, very few works have been done on studying the simulation of thin film membrane for CO_2 separation with sweeping. Hence, the main objectives of this study are modeling a thin film membrane for CO_2 separation with sweeping gas method. This includes studying the effects of different ratios of feeding flow rate and sweeping flow rate on the flow rate of CO_2 in the permeate side.

It is important to explain why using the computational fluid dynamics (CFD) method to carry out the proposed investigation. For a given type of membrane, the experimental data provided using standard designs for membrane testing is of global nature. We get the permeance, the pressure difference and flow rates. If we are to understand better the detailed concentration field on both sides of the membrane, it would be very expensive (need many sensors) and too intrusive. CFD can give us that information by solving for flow and mass transfer in the test cell. In addition, to change the design of the test cell, to predict the performance of membrane in industrial application (much larger dimensions) or to predict the performance of the membrane with the sweeping method (one subject treated in our paper), then, it is not need to waste time and money to make another setup or make larger membrane. The CFD tool is very useful to predict the membrane performance for different designs and different operating conditions. The classical (lumped model) equations can still be used in some cases but they do not give the full picture about the process as CFD.

2. Geometry of modeling

In this study, a thin film CO_2 separation membrane is modeled. Based on the experimentation equipment and process introduced by Gilassi and Rahmanian [15], the CFD (Computational Fluid Dynamics) modeling geometry and boundary conditions can be presented as shown in Fig. 1.

Different from the work done by Gilassi and Rahmanian [15], the direction of gas flow is parallel to the membrane in this study. The membrane is treated as a wall without thickness but has a thin thick mass source zone in the upstream side and an emerging mass source zone on the downstream side. Note here, the mass source for both fast gas and slow gas in sink zone is negative while in emerging zone is positive.

3. Governing equations

Apparently, the whole domain consists of three parts, the mixed gas zone (upper chamber above membrane), the membrane, and the permeate gases zone (lower part beneath membrane). Since the membrane is considered as a wall, hence the conservation equations are applied only on mixed gas zone and permeate gases zone. The continuity equation is expressed by Equation (1).

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = S_m \tag{1}$$

here, ρ, $\vec{v}$, and S_m are the density, velocity and source terms of gases, respectively.

The momentum equation for gases can be written as following in Equation (2).

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla \cdot (\rho \vec{v}\vec{v}) = -\nabla P + \mu \nabla^2 \vec{v} + \frac{\mu}{3}\nabla(\nabla \vec{v}) + \rho \vec{g} + \vec{F} \tag{2}$$

here, P is the pressure of gases. $\vec{g} = -9.81 m/s^2$ is the acceleration of gravity. $\vec{F}$ is the external forces and taken as 0. Considering the model as laminar flow, μ is the mass weighted-viscosity of mixed gases.

The energy equation to solve for the temperature field is written in Equation (3).

$$\frac{\partial}{\partial t}(\rho h) + \nabla \cdot (\rho \vec{v} h) = \nabla \cdot (k \nabla T) + \nabla \cdot \left(\sum_j h_j \vec{J}_j \right) + S_h \tag{3}$$

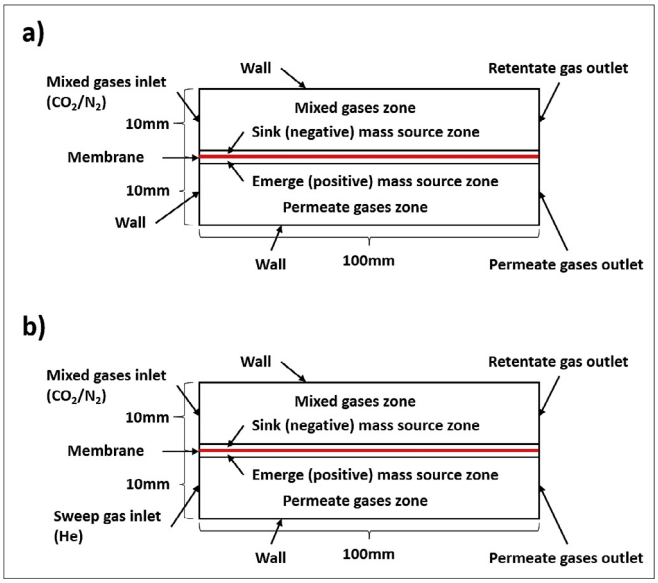

Fig. 1. Schematics of modeling geometry. a) vacuum in permeate gas outlet and b) sweep gas in permeate gases zone. Note that figures are scaled for better display.