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Wetting phenomenon in membrane contactors – Causes and prevention

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ABSTRACT

Gas–liquid membrane contactors are promising alternatives to conventional absorption technologies. However, in spite of their important advantages, such systems suffer from gradual wetting of porous membranes with liquid absorbents. This review focuses on the wetting phenomenon, which is the main concern for long-term operation of CO_2 absorption in membrane contactors and has therefore an important impact on industrial applications. The impact of membrane wetting on mass transfer resistance and absorption efficiency, the effect of influencing parameters including absorbent (operational conditions, type and concentration) and membrane (hydrophobicity, pore size and porosity) properties on wetting phenomenon, as well as different methods to prevent membrane wetting, along with their advantages and drawbacks are discussed in detail.

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1. Introduction

Capture of carbon dioxide (CO_2), the major greenhouse gas responsible for climate changes, has been a research focus in recent years [1]. A wide variety of CO_2 capture techniques have been proposed, including absorption, adsorption, cryogenic distillation and membrane techniques [2–4]. Among these, absorption in liquids (absorbent solutions) is the most well-established technology due to its highest CO_2 removal efficiency (up to 90%) [5]. However, absorption columns (bubble columns, packed columns and fluidized beds) suffer from several disadvantages such as large space occupancy, high capital cost, high tendency for corrosion and a variety of operational problems including liquid channeling, flooding, entrainment and foaming [6–8]. To overcome the aforementioned problems, gas–liquid membrane contactors (MC) have been proposed as a promising alternative. MCs involve the transfer of CO_2 through a nonselective porous membrane, followed by its absorption into a liquid absorbent. This technology is integrated to exploit the benefits of both absorption (high selectivity) and membrane separation (modularity and compact structure) [9], and offers several advantages such as: operational flexibility, independent gas and liquid flows, high surface area to volume ratio, compact size, easy scale-up and modularity [5]. On the negative side, membranes introduce an additional resistance (the membrane resistance) to the overall mass transfer process, which becomes more significant when membrane pores are wetted with liquid absorbents [10], leading to the deterioration of CO_2 absorption flux in long-term operation. Kreulen and Smolders [11] were the first to suggest that the wetting of membrane pores significantly impacts mass transfer coefficients in the membrane module, leading to a sharp increase in membrane resistance and a rapid decline of absorption performance.

In order to have a good understanding of the wetting mechanism and its effects on CO_2 capture efficiency, this paper presents a comprehensive review on wetting phenomenon from two main aspects: (i) wetting causes and (ii) wetting preventions. These aspects embrace the wetting characteristics of membranes and the effect of influencing parameters on wetting tendency of membranes in MC, as well as the approaches to prevent membrane wetting.

2. Mass transfer resistance in MC and membrane wetting

According to the film theory, the overall mass transfer in a gas–liquid membrane contactor consists of three resistances in series: the resistance of the gaseous phase boundary layer ($1/k_G$), the membrane resistance ($1/k_m$) and the resistance of the liquid the phase boundary layer ($1/k_L$) (Fig. 1) [12,13]. The overall mass transfer resistance, based on the gas phase ($1/K_{OG}$) in a hollow fiber MC is given by:

$$\frac{1}{K_{OG}} = \frac{d_O}{k_G d_i} + \frac{d_O}{k_m d_{lm}} + \frac{1}{m k_L} \tag{1}$$

where k_G is the gas side mass transfer coefficient (m/s); k_m is the membrane mass transfer coefficient (m/s); k_L is the liquid phase mass transfer coefficient (m/s); d_O is the outer diameter of hollow fiber membrane (m); d_i is the inner diameter of hollow fiber membrane (m); d_{lm} is logarithmic mean diameter and m is the distribution coefficient between gas and liquid phase (–). The individual mass transfer coefficients, k_G and k_L, are mainly determined by the geometry and flow conditions in the membrane contactor and various correlations are available in the literature to calculate them [14–16].

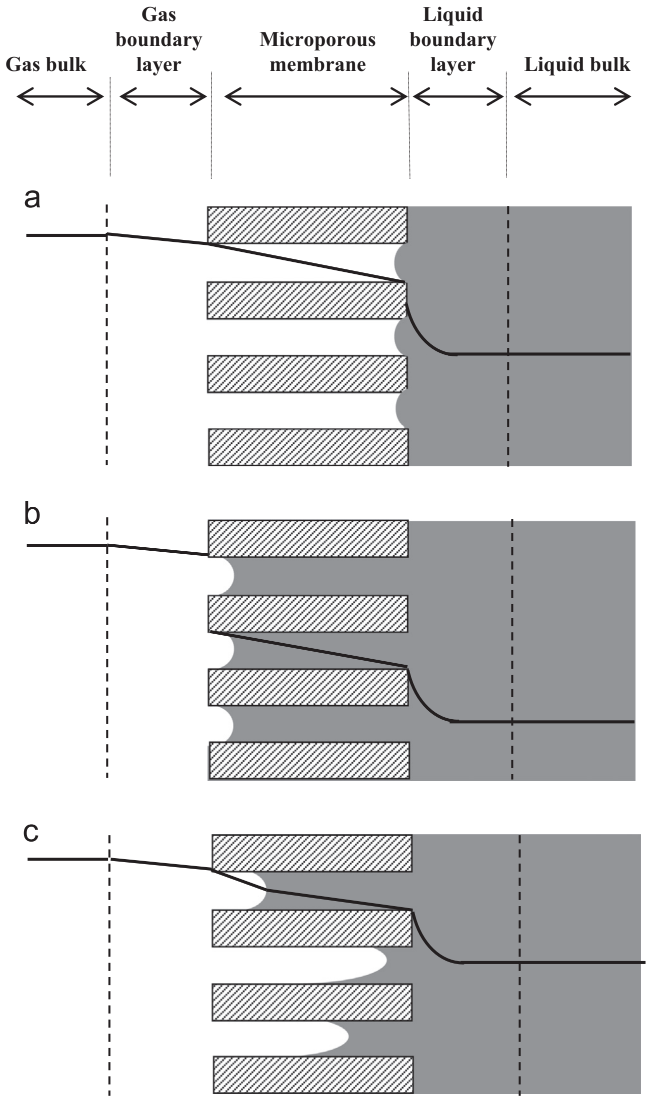

Fig. 1. Operation modes and corresponding mass transfer resistances in a hydrophobic microporous membrane: (a) non-wetting patterns, (b) overall wetting mode and (c) partial-wetting mode.

The membrane mass transfer resistance, as an additional resistance, should be taken into account, as it is significantly affected by wetting. Since convection in the membrane pores can be neglected, the mass transfer resistance of the membrane is entirely determined by solute diffusion in membrane pores that are filled with either gas or liquid. In ideal conditions, membrane pores are filled only with gas and the membrane mass transfer resistance of the gas-filled membrane pores can be estimated from [11]:

$$\frac{1}{k_{mg}} = \frac{\delta}{D_O}\frac{\tau}{\varepsilon} \tag{2}$$

where k_{mg} is the mass transfer coefficient through the gas-filled pores, while ε, τ and δ are the membrane porosity, tortuosity and thickness (which can also be assumed as the total pore length), respectively. D_O is the overall diffusion coefficient through membrane pores and is given by:

$$\frac{1}{D_O} = \frac{1}{D_{ij}} + \frac{1}{D_{kj}} \tag{3}$$

where D_{ij} and D_{kj} are diffusion coefficients for molecular and Knudsen diffusion through membrane pores respectively, and can be estimated using membrane and gas properties [10,16].