



Membrane evaporation of amine solution for energy saving in post-combustion carbon capture: Wetting and condensation



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ABSTRACT

A membrane evaporation system for energy penalty reduction in liquid absorbent based carbon capture and the effects of operating parameters (i.e. evaporation temperature, and gas/liquid flow rates) on mass and heat transfer are systematically investigated. It is found that monoethanolamine (MEA) vapor flux is approximately one order of magnitude lower than water vapor flux for membrane evaporation of 30 wt% MEA solution. Heat flux across the membrane is closely associated with mass transfer and is also influenced by the evaporation efficiency. Experimental results show that membrane wetting and vapor condensation occurs during the evaporation of MEA solution. Both evaporation temperatures and liquid flow rates play important roles in membrane wetting via changing the pressure on the liquid side. Slight wetting may decrease both mass transfer and the associated convective heat transfer across the membrane, but it can also provide benefit by preventing CO₂ absorption into the lean solvent. The occurrence of vapor condensation on the gas side is determined by the gas flow rate. Vapor condensation occurs at low gas flow rates but it will not be a significant operational issue in the membrane evaporator application as long as condensation occurs within the desorber where the latent heat is released and recovered.

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1. Introduction

Capture of carbon dioxide, the major greenhouse gas responsible for human-induced climate change, has attracted growing interest in recent years [1–3]. A number of technologies have been intensively investigated for carbon capture, including reactive liquid absorption [4], solid adsorption [5] and membrane based separation [6–8]. Among these, the state-of-the-art capture technology is still based on liquid absorbents which chemically react with CO₂, offering highest CO₂ removal efficiency (up to 90%) [2,9]. However, traditional absorption columns (e.g. packed columns, bubble columns and fluidized beds) suffer from several drawbacks such as large space occupancy, high tendency of corrosion, flooding, foaming and channelling [10–12]. To overcome these issues, membrane contactors have been proposed as a promising alternative for CO₂ capture [8,13–19].

Integrating the advantages of liquid absorption (high selectivity) and membrane separation (modularity and compactness), membrane contactors have some noticeable advantages, such as surprisingly high interfacial area, operational flexibility due to

independent gas/liquid flows and linear scale-up [20,21]. However, membrane contactors also suffer from a major problem – wetting [22]. The resistance of wetting can be evaluated by the critical wetting pressure, also called liquid entry pressure (LEP) or breakthrough pressure. LEP can be expressed by the Laplace–Young equation [23]

$$LEP = \frac{-4\gamma \cos \theta}{d_{\max}} \quad (1)$$

where γ is the liquid surface tension, θ is the contact angle between the liquid and the membrane surface, and d_{\max} is the maximum pore diameter.

From Eq. (1), it is obvious that wetting is associated with both membrane properties (e.g. pore size and hydrophobicity) and liquid absorbent properties (e.g. surface tension of the absorbent). Several hydrophobic porous membranes with low surface energy, such as PTFE (polytetrafluoroethylene), PP (polypropylene), and PVDF (polyvinylidene difluoride) have been proposed for CO₂ absorption in membrane contactors [24–26]. Nevertheless, these porous membranes suffer from severe pore wetting over prolonged period of operation [27,28]. Wetting significantly increases the mass transfer resistance and thus reduces the absorption efficiency. To prevent membrane wetting, a variety of methods such

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as selection of suitable membrane-absorbent combination [24], optimisation of operational conditions [29], use of composite membranes with dense skin layers [27,30,31] and surface modification [32] have been suggested. In practice, wetting is almost an unavoidable issue in long term operation even though the methods mentioned above can postpone the occurrence of wetting [22].

To take advantages of the benefits of liquid absorption and membrane contactors, we propose a *membrane assisted liquid absorbent regeneration* (MALAR) process [33], which is an innovative use of membrane contactors in liquid absorbent based CO₂ capture processes. MALAR aims to achieve efficient energy control by employing membrane contactors (i.e. a membrane evaporator and a membrane condenser) to restrict the heat within the desorber; such heat is generally undesirably lost. MALAR can efficiently integrate heat recovery in the liquid absorbent regeneration process. The use of membranes for direct heat transfer via evaporation or condensation enables quite small approach temperatures which would be unachievable and/or uneconomical with conventional heat exchangers. The compactness of the membrane contactors further adds to the achievement of small temperature differences and thereby a very energy efficient process. More details and explanations about the MALAR can be found in our previous study [34,35].

In the MALAR application envisaged here, both hydrophobic (operated in a non-wetted mode) and hydrophilic (operated in a wetted mode) membranes could be used in the contacting system. In the wetted mode, the mass transfer resistance increases dramatically but the heat transfer function is not significantly affected and the liquid will be contained in the stripping column and mixed with the liquid absorbent already present. Therefore, slight wetting that can be a major problem in a conventional membrane contactor, will not be a big issue in the MALAR application.

In this study, we focus on the membrane evaporator unit as shown in Fig. 1. CO₂-rich solvent forms after the solvent absorbs CO₂ from the flue gas, and then it can be split into two streams. One stream goes to the desorber via the lean/rich heat exchanger, and the other stream flows to the desorber without heat exchanging. After CO₂ is released from the desorber, CO₂-lean solvent goes to a membrane evaporator. Without the membrane evaporator, the temperature of the CO₂-lean stream after heat exchanging is still higher than the absorption temperature (lowering absorption

efficiency). To improve the absorption efficiency, a low temperature is preferred and a cooling system after the heat exchanger is required. Such cooling undesirably consumes the thermal energy (from the desorber) in the process.

The membrane evaporator aims to recover part of the heat of the CO₂-lean stream back to the desorber and to achieve efficient energy control. Mass and heat transfer performance of the membrane evaporator was experimentally and theoretically estimated in our previous study [34]. This study focuses on the two interesting and important phenomena in the process: wetting and condensation. Experiments on membrane evaporation of a liquid absorbent are carried out in this work. Monoethanolamine (MEA) is selected as the model absorbent. A flat sheet microporous PTFE membrane is used in the membrane contacting system because of its excellent thermal and chemical stabilities. In membrane evaporation of MEA solution, two important phenomena: wetting and condensation are investigated.

2. Materials and methods

2.1. Absorbent and membrane

MEA (Sigma–Aldrich, purity > 99.0%) was selected as the model absorbent. 30 wt% MEA solution was prepared by mixing MEA with deionized water (conductivity $\approx 6.48 \mu\text{S}/\text{cm}$). A flat sheet hydrophobic membrane (Dagong Co. Ltd., China) was used as the membrane evaporator. According to the supplier, the membrane consists of a polytetrafluoroethylene (PTFE) active layer (20 μm) and a polypropylene (PP) support layer (140 μm) with a grid-like structure. The nominal pore size of the membrane is 0.2 μm . More details about the membrane can be found in our previous study [34].

2.2. Membrane properties

The membrane properties have been characterised in our previous study [34]. Measurements show that water and MEA (30 wt%) entry pressures of the membrane are 165 and 138 kPa, respectively. The membrane has a water contact angle of 114°, and an MEA (30 wt%) contact angle of 111°.

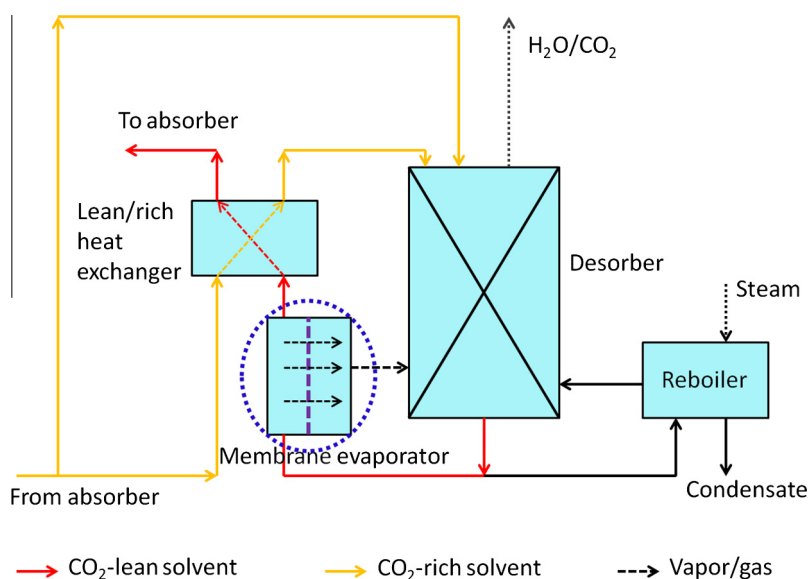


Fig. 1. Schematic illustration of the membrane evaporator system.

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