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# Membrane evaporation of amine solution for energy saving in post-combustion carbon capture: Performance evaluation

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## ABSTRACT

In this study, we propose a membrane evaporation system for energy penalty reduction in post-combustion carbon capture (PCC) and carry out membrane evaporation of amine solutions. The effects of some key factors (i.e. evaporation temperature, gas and liquid flow rates and solvent concentration) on mass and heat transfer are systematically investigated. It is found that both evaporation temperature and gas flow rates have significant influences on vapor and heat transfer, while liquid flow rates have limited effect on mass and heat transfer in membrane evaporation. The vapor and recovered heat fluxes increase exponentially with the rise in evaporation temperature, and increase linearly with the rise in gas flow rates. The increase in evaporation temperature and gas flow rates also significantly improves the evaporation efficiency and heat recovery. Mass and heat transfer rates decrease as the concentration of the solvent increases because of the reduced vapor pressure of the liquid at higher concentration. It is estimated that the recovered heat flux can be up to  $32 \text{ MJ m}^{-2} \text{ h}^{-1}$  and heat recovery can be over 40% when the gas/liquid flow rate ratio is 150. Therefore, the proposed membrane evaporation system has great potential to save considerable energy in large-scale PCC pilot plant operation.

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## 1. Introduction

$\text{CO}_2$  capture and storage (or sequestration) (CCS) is recognized as one of the most important strategies to combat human-induced climate change [1–3]. In the CCS chain the separation (i.e.  $\text{CO}_2$  capture) stage is energy intensive, accounting for around 70% of the total costs [4]. Generally carbon capture can be realised by three ways: post-combustion carbon capture, pre-combustion carbon capture and oxyfuel combustion. Among them, post-combustion carbon capture has the greatest potential to be readily used for large-scale carbon capture in the near future, because it can be retrofitted to the existing units in power plants around the world.

Although various technologies such as liquid chemical absorption [2], solid adsorption [5] and membrane separation [1,6] have been intensively investigated for carbon capture, the state-of-the-art capture technology is still based on liquid absorbents which chemically react with  $\text{CO}_2$  [7,8]. Since 2007, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) working with power companies has established 3 absorbent based post-combustion carbon capture pilot plants around Australia, with capture capacities ranging from 100 to 500 kg/h  $\text{CO}_2$  [9]. By

operating these carbon capture pilot plants, we have gained considerable knowledge and experience in terms of energy performance [8,10], process modification [11–13] and absorbent development/validation [14,15].

However, carbon capture is still an energy intensive technology for large-scale commercialization. Typical output (i.e. plant power) reductions for 90% capture of  $\text{CO}_2$  at a power station are around 30% [8]. It is therefore necessary to improve the absorbent regeneration process by minimizing thermal energy required in the desorber. To achieve efficient energy control, we propose a novel *membrane assisted liquid absorbent regeneration* (MALAR) process by employing membrane contactors (i.e. a membrane evaporator and a membrane condenser) [16] to restrict the heat within the desorber (Fig. 1); such heat is generally undesirably lost.

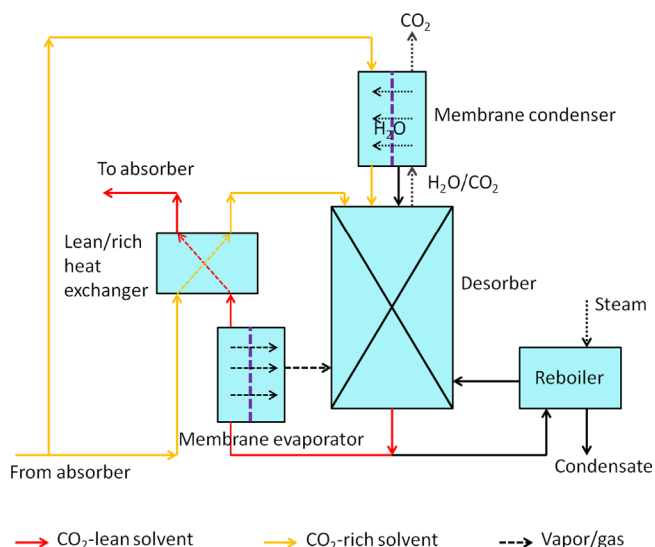
As illustrated in Fig. 1, the MALAR system mainly have two parts: a membrane condenser and a membrane evaporator. After a solvent absorbs  $\text{CO}_2$  from the flue gas, it becomes rich  $\text{CO}_2$  absorbent and can be split into two streams. One stream (S1) goes to a membrane condenser and the other stream (S2) flows to the lean/rich heat exchanger. On top of the desorber, steam (i.e. water vapor) saturated  $\text{CO}_2$  stream goes to a membrane condenser. After membrane condensation, partial water vapor associated with its latent heat can be recovered by the relatively cold stream (S1). At the bottom of the desorber, a membrane evaporator is used to recover partial heat of the lean  $\text{CO}_2$  stream back to the desorber. Without the membrane evaporator, the temperature of the lean

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**Fig. 1.** Schematic illustration of the Membrane Assisted Liquid Absorbent Regeneration (MALAR) system.

CO<sub>2</sub> stream after heat exchanging is still higher than the absorption temperature (lowering absorption efficiency). Thus, a cooling system after the heat exchanger is required and it wastes the heat in the process.

The proposed innovation aims to efficiently integrate heat recovery in the liquid absorbent regeneration process. This is achieved by the use of membranes for transfer of heat using condensation and evaporation processes. Fundamentally, the membrane condenser and evaporator are used as heat exchangers for heat recovery. Both mass and heat transfer occurs in such membrane heat exchanger that is different from the conventional heat exchanger (where only heat transfer occurs). The process concept is an entirely new one utilizing membranes as gas–liquid contactors in such a way that the (common) occurrence of liquid leakage through the membrane is not an issue [16].

In the MALAR process energy is recovered via transfer of steam through a membrane. In the membrane condenser latent heat is recovered from the wet CO<sub>2</sub> product into a portion of the cold CO<sub>2</sub>-rich liquid absorbent; in the membrane evaporator latent heat is recovered from the hot CO<sub>2</sub>-lean absorbent into the stripping column (Fig. 1). 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 [17–19].

In a membrane contactor, a membrane is normally used to contact a gas flow with a liquid flow. Such operations often suffer from minor amounts of liquid permeating through the membrane to the gas phase [20–22]. This liquid is subsequently carried away by the gas flow, which is generally not desired, particularly if the gas enters the atmosphere. It will furthermore hamper the efficient transfer of components between the two phases. In the MALAR application envisaged here, liquid leakage is not critical as 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.

In this study, we focus on the membrane evaporator part and carry out membrane evaporation of a liquid absorbent. Monoethanolamine (MEA) is selected as the model absorbent. A flat sheet microporous polytetrafluoroethylene (PTFE) membrane is used in the membrane contacting system because of its

excellent thermal and chemical stabilities. The influences of some factors (e.g. evaporation temperature, gas and liquid flow rates, and absorbent concentration) on mass and heat transfer are systematically investigated.

## 2. Materials and methods

### 2.1. Absorbent and membrane

30 wt% MEA solution was selected as the model absorbent in membrane evaporation. A flat sheet hydrophobic membrane (Dagong Co. Ltd., China) was used in the membrane evaporation experiments. According to the supplier, the membrane consists of a polytetrafluoroethylene (PTFE) active layer and a polypropylene (PP) support layer with a grid-like structure. The nominal pore size of the membrane is 0.2 μm.

### 2.2. Membrane characterization

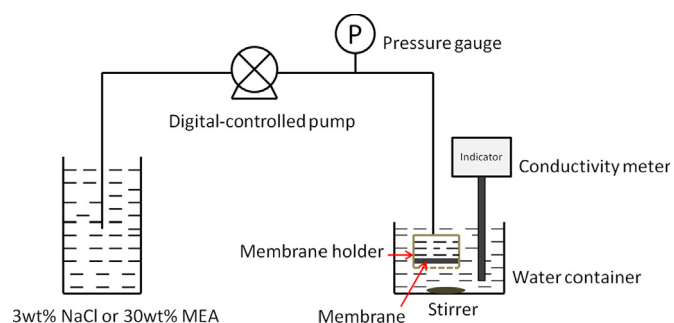
The membrane morphology was characterized by Field Emission Gun Scanning Electron Microscopy (FEG-SEM) with a Philips XL30 system. The membrane sample was coated with a thin gold layer to make the film surface conductive before imaging. Thicknesses of the active layer and support of the membrane were measured with a digital micrometer (Mitutoyo, Japan). Water contact angle of the membrane active (PTFE) layer was measured by a contact angle analyzer (DataPhysics Instruments GmbH, Filderstadt, Germany).

Both pure water and 30 wt% MEA solution were used for liquid entry pressure measurement at room temperature (~25 °C). The measurement setup is described in Fig. 2. 3 wt% of NaCl and 30 wt% of MEA solutions were respectively used as the liquid. The system pressure is maintained by a digital-controlled gear pump (Process Pump, Australia). A piece of membrane was fitted into a membrane holder with a diameter of 25 mm that is placed in a deionized water container. The conductivity of the water was measured in a continuous mode. The pressure was increased step by step (by 2 psi or 13.8 kPa) and was maintained for at least 5 min for each step. The pressure at which the conductivity of the water starts to change dramatically is regarded as the liquid entry pressure.

The porosity of the membrane was evaluated based on the wetting method [23]. Pure water and pure acetone were used as the non-wetting and wetting solutions, respectively. 50 mL volumetric flasks were used for volume determination. Results on the membrane properties were summarized in Table 1.

### 2.3. Experimental setup for membrane evaporation

Membrane evaporation experiments were conducted with a bench-scale membrane system [24]. The PTFE membrane cell has



**Fig. 2.** Experimental setup for liquid entry pressure measurement.

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