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# Transport membrane condenser for water and heat recovery from gaseous streams: Performance evaluation

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ABSTRACT

Using a tubular ceramic membrane as the transport membrane condenser for simultaneous water and heat recovery from gaseous streams is experimentally investigated in the current study. The effects of several important operational parameters (e.g. gas flow rate, coolant flow rate, transmembrane pressure and inlet gas temperature) on the process performance in terms of mass and heat transfer across the membrane are systematically studied. It is found that mass and heat transfer rates can be enhanced by increasing the gas flow rate, coolant water flow rate and the temperature of the inlet gas stream. To improve the water and heat recovery, a low gas flow rate but a high coolant flow rate should be maintained. Increasing the transmembrane pressure difference decreases the mass and heat transfer mainly due to the reduced inlet gas humidity, enthalpy and flow rate. However, water and heat recovery does not change significantly with the change in transmembrane pressure. 20–60% water recovery and 33–85% heat recovery are achievable when using cold water as the coolant. The mass transfer mechanism in membrane condensation is complex and needs further exploration. These findings offer significant implications in using transport membrane condensers for water and heat recovery from gas streams with high moisture.



## 1. Introduction

With the exponentially growing population and the depletion of natural resources, our world is experiencing more shortages in both water and energy than ever before [1,2]. High temperature gaseous streams containing water vapor associated with a large quantity of latent heat can be found in many industrial processes, such as fuel-fired power generation, wet scrubbing and water quenching. Generally, such streams are exhausted into the atmosphere, as a result of which considerable water and energy are lost. In fact, these gaseous streams may become a new source of both water and energy if recovery methods are economically and technically available [3].

Flue gas typically with high moisture from power plants is one of the most important gaseous streams, and it has attracted great interest as a promising source of water and energy [3–6]. In Europe, 14 international partners including universities, research institutes and companies have launched the CapWa project for capture of evaporated water from flue gas using membranes [4]. It is estimated that a power plant can be self-sufficient if 20% of the evaporated water in the flue gas can be recovered [7]. In the United States (US), Gas Technology Institute (GTI) has developed a new membrane technology, called transport membrane condenser (TMC), which has been used for waste heat and water recovery from the flue gas in coal-fired power plants [5,6,8]. It is demonstrated that the recovery of the exhausted water vapor can be 40% and an increase in energy efficiency can be over 5% [6]. Siemens has similar programs for water and energy recovery from flue gas [9,10]. For biomass-fired power plants, water and energy recovery can become more important and attractive due to the higher water content (i.e. 30–50%) in the flue gas [10].

There are several conventional waste heat recovery technologies, such as recuperators, regenerators, waste heat boilers and finned tube heat exchangers [3]. These technologies are often used for high grade (i.e. high temperature) heat recovery. Therefore, they have the temperature requirements and material constrains. Heat recovery from low-temperature gas streams by a conventional heat exchanger requires a large surface area. In addition, contaminants like $CO_2$, SOx and NOx within the gas stream may cause material corrosion problems during the recovery.

A number of methods, such as cooling with condensation, liquid and solid sorption and cryogenic separation, have also been employed for water recovery from gas streams [11]. However, each method has

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its own drawbacks. Condensation by conventional heat exchangers may suffer from the issues of acid contaminant corrosion. Chemical or physical sorption generally requires high regeneration cost. Cryogenic separation is a very energetic process that is typically used to separate gases with low boiling points. However, it is not economical for water recovery from gas streams due to the large boiling point difference between the gases and water.

The membrane condenser as a novel heat exchanger can overcome the disadvantages of conventional technologies in water and heat recovery from gas streams [6,11–13]. In addition, a membrane heat exchanger may have higher heat recovery efficiency than the conventional one because both mass and heat transfer occurs in the membrane heat exchanger. In spite of the great potential of membrane heat exchanger in water and heat recovery, there are insufficient studies on this new condensation technology.

This study explores the feasibility of employing a porous ceramic membrane with pore size on the nano-scale for simultaneous water and heat recovery from a gas stream with high water content. The effects of several important operational parameters (e.g. gas flow rate, coolant flow rate, transmembrane pressure and inlet gas temperature) on the mass and heat transfer across the membrane in terms of fluxes and recoveries are systematically investigated. The findings of this study offer significant implications in using transport membrane condensers for water and heat recovery from water vapor saturated gas streams.

## 2. Transfer mechanisms in membrane condensation

### 2.1. Condensation with hydrophobic membranes

Hydrophobic porous membranes can be utilized for gas and/or vapor separation (e.g. membrane distillation). The mechanisms of water and/or heat recovery from gas streams with hydrophobic porous membranes are illustrated in Fig. 1. In Fig. 1A, water vapor condensation occurs at the gas-membrane interface, and other gas components go through the porous membrane under a hydraulic pressure. After membrane condensation, liquid water on the gas side is ready to be collected for recovery. Based on this mechanism, a membrane condensation technology has been recently developed for water recovery from industrial gases [12,13]. To prevent membrane degradation and pore wetting, thermal and chemical stabilities of the membrane materials should be carefully considered when using this condensation technology [11].

In fact, hydrophobic porous membranes can be used for simultaneous water and heat recovery from gas streams when condensation occurs at the liquid-membrane interface as shown in Fig. 1B. The hydrophobic membrane is used as a gas/liquid contactor in this process. Under the driving force of water vapor partial pressure difference, water vapor in the gas stream transfers through the membrane and condenses into the cold liquid (generally water). This new type of membrane condenser can be very effective in heat exchanging (i.e. heat recovery) since both mass transfer and heat transfer (including convective and conductive) occur in the process. However, much attention should be paid to the undesirable condensation on the gas side or within the membrane pores when employing this condensation technology [14,15].

### 2.2. Condensation with hydrophilic membranes

Hydrophilic membranes are generally designed for liquid water transport (e.g. membrane evaporation). Fig. 2 illustrates the mass and heat transfer mechanisms across a hydrophilic porous membrane (A) and a hydrophilic dense membrane (B).

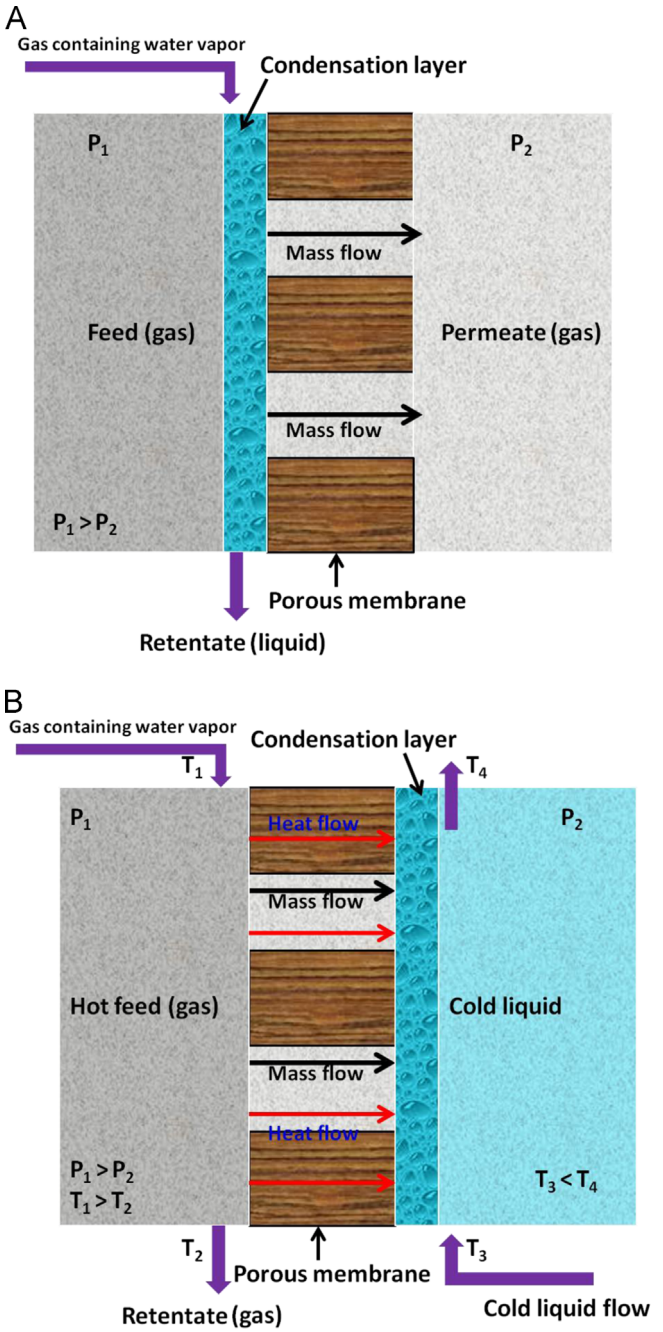


**Fig. 1.** Mass and heat in gas streams transfer across hydrophobic porous membranes: (A) condensation occurs at the gas-membrane interface; (B) condensation occurs at the liquid-membrane interface.

In Fig. 2A, a curved meniscus forms within the membrane pores when capillary condensation occurs in membrane condensation. Capillary condensation dominates the mass transfer mechanism when a hydrophilic membrane pore size is in the range of 2–50 nm [16,17]. GTI has developed a ceramic membrane condenser with a separation layer (pore size 6–8 nm) for heat recovery from coal-fired flue gas and achieved much higher permeate flux than the expected from gas phase transport [6]. The high water vapor transfer through the membrane is thought to be governed by a pseudo-liquid phase transfer (i.e. capillary condensation) [8]. More information on capillary condensation can be found in Ref. [18]. Heat transfer is realized by both thermal conduction (dependent on the thermal conductivity of the membrane material) and convective heat flow (dependent on the mass transfer rate).

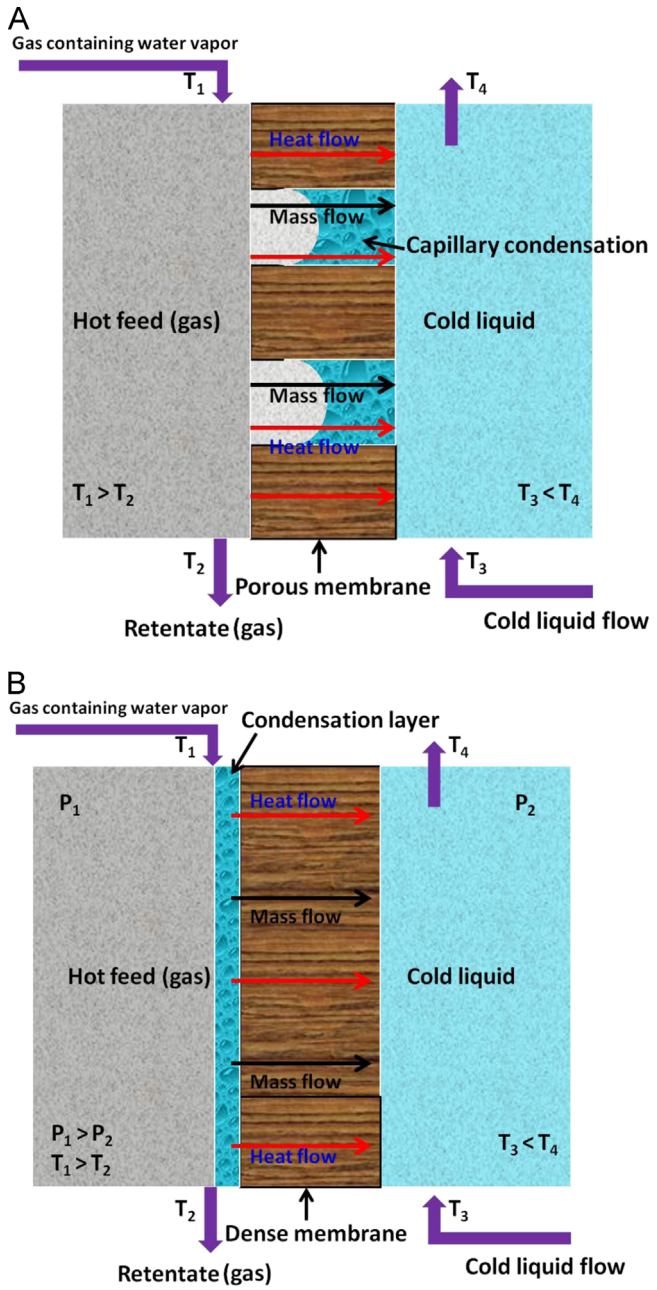


**Fig. 2.** Mass and heat in gas streams transfer across hydrophilic membranes: (A) capillary condensation occurs within the membrane pores; (B) condensation occurs at the gas-membrane interface.

When a hydrophilic dense membrane is used for water and heat recovery, water vapor condensation may occur on the gas side and then diffuse through the membrane into the cold liquid (Fig. 2B). In this case, the classical solution–diffusion model [19] governs the mass transfer in which a hydraulic pressure difference across the membrane may improve the transfer rate. Such transfer mechanism for heat recovery and/or humidity control has been widely employed in air conditioning systems where membranes generally undergo moderate temperature [20–26]. More thermally and chemically stable membrane materials should be taken into account when using hydrophilic dense membrane for water and heat recovery from high temperature gas streams.

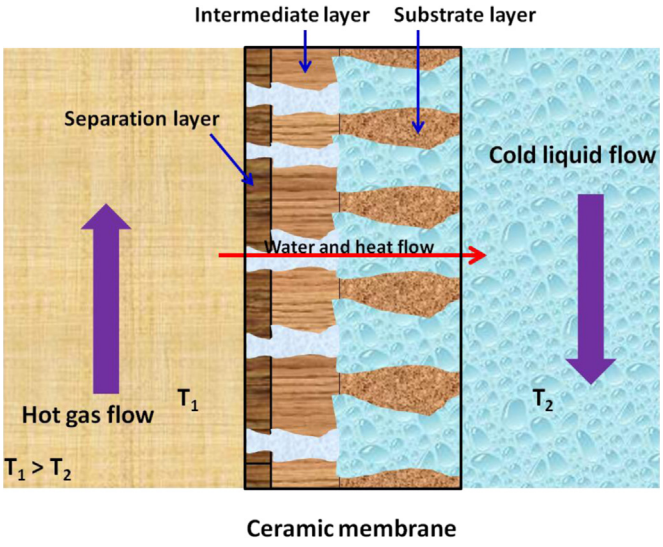


**Fig. 3.** Schematic diagram of the membrane structure including a separation layer, an intermediate layer and a substrate layer.

**Table 1**
Properties of the ceramic membrane.

| Membrane shape | Separation layer | | | Length | Effective area |
|---|---|---|---|---|---|
| | Orientation | Pore size | Thickness | | |
| Tubular | Inner | 6–8 nm | 1 μm | 0.085 m | 0.0021 $m^2$ |

## 3. Materials and methods

### 3.1. Membrane preparation and characterization

Titania particulate sol was prepared by using acid-catalyzed colloidal sol–gel route with titanium (IV) isopropoxide as a precursor, as described in detail in Ref. [27]. This sol was subsequently deposited on a commercial tubular α-$Al_2O_3$ macroporous support (OD: 12 mm, ID: 8 mm, length: 85 mm, average pore size: 20 nm), provided by Jiangsu Jiuwu Hi-tech Co. China) through the dip-coating method [28]. After drying, the titania membrane was calcined at 400 °C for 3 h.

Schematic illustration of mass and heat transfer across the membrane is described in Fig. 3. The membrane consists of three layers: a separation layer, an intermediate layer and a substrate. The separation layer is on the inner tube side of the tubular membrane. Nominal pore size of the separation layer was determined by the gas bubble method [29,30]. The properties of the titania membrane are shown in Table 1.

### 3.2. Experimental setup for water and heat recovery

Membrane condensation experiments for water and heat recovery were carried out with a bench-scale condensation system as described in Fig. 4. Air was pumped into a steam generation system and the air flow rate was monitored by a gas flow meter. After humidification, water vapor saturated air went to a tubular ceramic membrane. A humidity transmitter (Vaisala, Finland) and a thermocouple were used to measure the inlet gas stream humidity and temperature, respectively. Before the ceramic membrane, the stainless tubing of the gas stream was thermally insulated and heated to the required temperatures by heating belts with a temperature

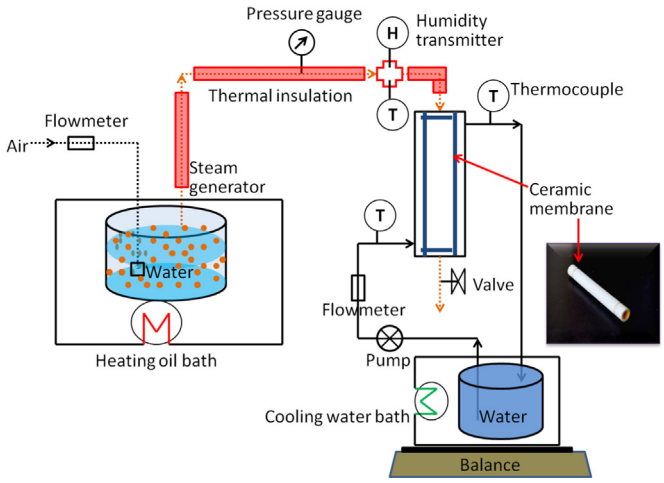


**Fig. 4.** Shematic diagram of the experimental setup for water and heat recovery. $H$=Humidity transfermitter, $T$=thermocouple.

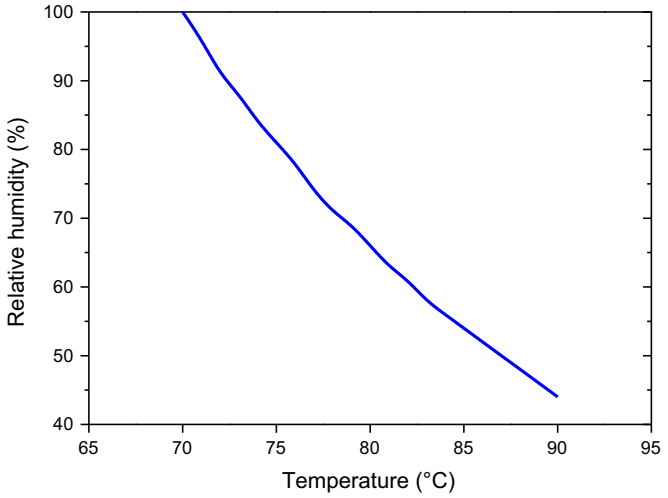


**Fig. 5.** Relative humidiy as a function of temperature. Simulation is obtained for air by the Vaisala humidity calculator (version 3.0).

controller. The hot gas stream contacted the separation layer on the tube side of the membrane, and cold water was countercurrently circulated on the shell side of the membrane.

Temperature of the coolant water was maintained stable at room temperature (~33 °C) with a cooling water bath. The flow rate, inlet and outlet temperatures of the water were measured for heat transfer determination. The weight change of the liquid water was monitored with a balance for mass transfer determination. Liquid coolant water temperature was maintained with a cooling water bath. Data recording was started once the mass transfer and heat transfer became relatively stable (i.e. mass and heat transports became balanced). The time for mass and heat balancing varied (from 20 to 50 min) with the experimental conditions. For each experimental condition, the weight and temperature data were recorded for at least 30 min at a time interval of 5 min after the mass and heat transfer became relatively stable. The error bar was used to reflect the data deviation during different time intervals. The uncertainties for the measurements were: gas side temperature ± 2.5%, liquid side temperature ± 6%, humidity ± 2%, gauge pressure ± 2.5%, and flow rates ± 3%.

Although industrial gas streams may not be always saturated, saturated gas streams have been selected in similar studies [11,12]. In fact, saturated gas streams can represent unsaturated ones since the relative humidity of a gas is highly temperature sensitive as shown in Fig. 5, namely, the switch between saturated gas and unsaturated gas can be easily realized by the change in gas temperature.

### 3.3. Flux and recovery determination

In the membrane heat exchanger, mass and heat transfer occurs simultaneously across the ceramic membrane. Permeate flux, heat flux, water recovery and heat recovery are four important parameters for assessing the process performance.

Water flux ($J_w$) and heat flux ($q_w$) across the membrane can be respectively expressed by

$$J_w = \frac{\Delta W}{\Delta t A} \tag{1}$$

$$q_w = \frac{C\dot{m}_l \Delta T + \dot{m}_T h(t)}{A} \tag{2}$$

where $\Delta W$ is the weight change (kg) of the liquid water during a time period $\Delta t$ (h), $A$ is the effective membrane area ($m^2$), $C$ is the specific heat capacity of water (kJ/kg°C), $\dot{m}_l$ is the liquid coolant (water) flow rate (kg/h), $\Delta T$ is the temperature change of the liquid water (°C), $\dot{m}_T$ is the water transfer rate, $\Delta W/\Delta t$ (kg/h), and $h(t)$ is the water specific enthalpy (kJ/kg) at temperature $t$. Thus, the unit of mass flux is kg/$m^2$ h and the unit of heat flux is kJ/$m^2$ h.

Water recovery ($\gamma$) in the membrane condenser can be described as

$$\gamma(\%) = \frac{\Delta W}{W_{loss}} \times 100 \tag{3}$$

where $W_{loss}$ is the weight loss of the evaporated water from the steam generator during the same time period as $\Delta W$. $W_{loss}$ can be experimentally determined by the decline of the water level in the steam generator.

Heat recovery ($\eta$) in the membrane condensation system can be determined by

$$\eta(\%) = \frac{U_{obtain}}{U_{inlet}} \times 100 = \frac{q_w A}{h\Delta_{inlet}} \times 100 \tag{4}$$

where $U_{obtain}$ is the obtained heat transfer rate (kJ/h) across the membrane, $U_{inlet}$ is the heat flow rate (kJ/h) of the inlet gas stream to the membrane module, $h$ is the specific enthalpy (kJ/kg) of the gas stream (i.e. water vapor saturated air), and $\dot{m}_{inlet}$ is the gas stream flow rate (kg/h). Both h and $\dot{m}_{inlet}$ can be obtained with the help of the Humidity Calculator software (version 3.0) from Vaisala, Finland.

## 4. Results and discussion

### 4.1. Effect of air flow rate

Fig. 6 presents the effect of the air flow rate on mass and heat transfer in membrane condensation. It is obvious that both water flux and heat flux increase dramatically with the increase in the air flow rate. This suggests that the effect of air flow rate on the mass and heat fluxes are significantly influenced by the magnitudes of the air side transfer resistance relative to the total resistance. Water vapor quantity in the gas stream increases with increasing air flow rates when the humidity of the gas stream (i.e. relative humidity 100%) is unchanged at a given temperature. As a result, more water vapor goes to the membrane module and higher permeate flux can be achieved at higher air flow rate. From Fig. 6, it can be seen that the water flux increases by approximately 100% (from 7.8 to 15.8 kg/$m^2$ h) when the gas flow rate increases from 1 to 4 L/min. Heat flux has similar change trends with increasing

the air flow rate as the convective heat transfer across the membrane is closely associated with the mass transfer. Heat flux increases from 23 to 40 MJ/m$^2$ h when the gas flow rate increases from 1 to 4 L/min.

Although mass flux and heat flux increase with the rise in the air flow rate, the changes in water recovery and heat recovery do not follow the same trend. On the contrary, water and heat recoveries decrease with the increase in the air flow rate as shown in Fig. 7. This suggests that higher water and heat recoveries can be achieved at a lower air flow rate when there is a longer residence time between the gas stream and the membrane module [11]. Residence time plays an important role in mass and heat recoveries. Longer residence time generally results in higher water and heat recoveries. This suggests that higher water and heat recoveries can also be reached by using longer membranes in addition to maintaining a lower gas flow rate.

In Fig. 7, it is obvious that the heat recovery decline is much more significant than the water recovery reduction with increasing the air flow rate. This can also be explained by the shorter contacting time with the membrane at higher air flow rate. Shorter contacting time causes more unrecovered energy within the outlet gas stream, leading to a lower heat recovery.

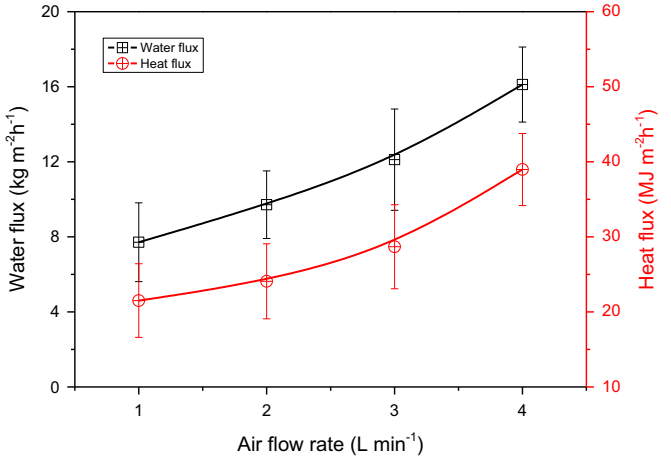


**Fig. 6.** Effect of air flow rate on water and heat fluxes. Experimental conditions: water vapor saturated air as the gas stream; gas mixture temperature 75 °C; liquid flow rate 5 L/h; liquid side gauge pressure 0; gas side gauge pressure 0.04 MPa; effective membrane area 0.0021 m$^2$.

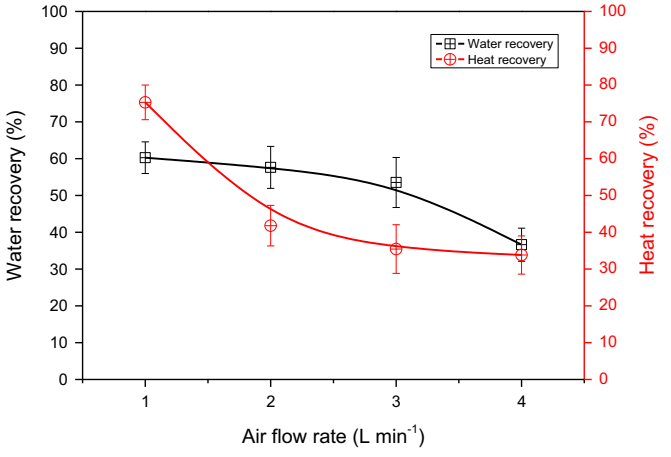


**Fig. 7.** Effect of air flow rate on water and heat recoveries. Experimental conditions: water vapor saturated air as the gas stream; gas mixture temperature 75 °C; liquid flow rate 5 L/h; liquid side gauge pressure 0; gas side gauge pressure 0.04 MPa; effective membrane area 0.0021 m$^2$.

It should be noted that the heat recovery from the gas stream can never reach 100%. The outlet gas stream after membrane condensation always has some enthalpy no matter how low the outlet gas temperature is. When the outlet gas temperature and humidity is still high after condensation, it will cause a relatively low heat recovery. Such situations can be found when the inlet gas flow rate is high (Fig. 6) or the inlet gas temperature is high (Fig. 13).

### 4.2. Effect of water flow rate

As the coolant for heat collection, the flow rate of the liquid water has a significant effect on the mass and heat fluxes as depicted in Fig. 8. Both water flux and heat flux increase with the increase in the water flow rate. Similar findings in membrane condensation have been reported [6]. However, heat flux improvement is much more dramatic, almost linearly with increasing the water flow rate. This may be resulted from the conductive heat transfer in addition to the convective heat transfer across the membrane. The almost linearly increased heat flux with the rise in water flow rate also indicates that the effect of water flow rate on the heat flux is largely affected by the magnitudes of the water side thermal resistance relative to the total thermal resistance.

It is also found that the outlet gas temperature after condensation drops with the increase of the water flow rate as presented in Table 2. It is expected that the humidity of the outlet gas also declines with increasing the water flow rate as the mass transfer is enhanced with the rise in water flow rate. Therefore, the temperature and humidity determined enthalpy of the outlet gas stream is supposed to reduce significantly, leading to an obviously increased heat recovery as shown in Table 2 and Fig. 9. On the other hand, increased water flow rates mean shorter residence time, leading to

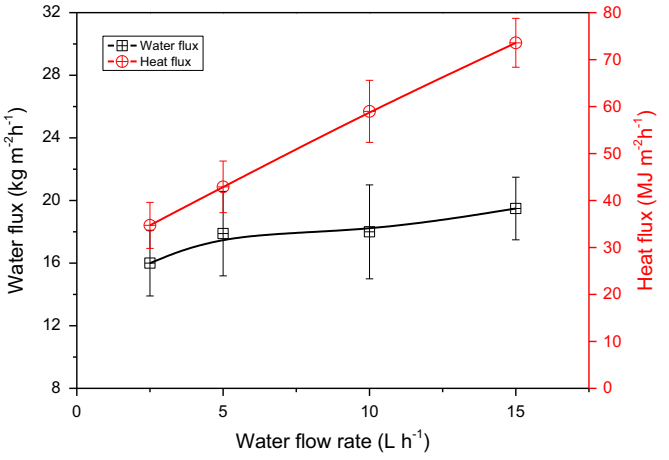


**Fig. 8.** Effect of water flow rate on mass and heat fluxes across the membrane. Experimental conditions: water vapor saturated air as the gas stream; gas mixture temperature 77 °C; air flow rate 3 L/min; liquid side gauge pressure 0; gas side gauge pressure 0.04 MPa; effective membrane area 0.0021 m$^2$.

**Table 2**
Outlet water and gas temperatures after membrane condensation at different water flow rates (inlet water temperature 33 °C and inlet gas temperature 77 °C).

| Water flow rate (L/h) | Outlet water temperature (°C) | Outlet gas temperature (°C) | Heat recovery $\eta$ (%) |
|---|---|---|---|
| 2.5 | 39.4 | 59.7 | 40.3 |
| 5 | 38.2 | 58.8 | 49.8 |
| 10 | 37.4 | 57.8 | 68.4 |
| 15 | 35.4 | 56.9 | 85.4 |

lower outlet water temperatures (Table 2). This will increase the driving force and thus mass and heat transfer rates.

Water recovery and heat recovery have similar change trends as fluxes with the change in water flow rate (Fig. 9). Water recovery from the gas stream increases slightly from 50% to 60% when the water flow rate is increased from 2.5 to 15 L/h. In the same water flow rate range, however, the heat recovery increases dramatically from 40% to 85%. This indicates that increasing the coolant flow rate can effectively improve the heat recovery efficiency. This has been theoretically confirmed by an analytical model. In the modeling, Jeong et al. introduced a term called "condensation efficiency" for performance evaluation and reported that the ratio of the coolant water flow rate to the inlet flue gas flow rate was the most important parameter for condensation efficiency evaluation [31].

### 4.3. Effect of transmembrane pressure

Fig. 10 shows the effect of transmembrane pressure on the permeate flux and heat flux in membrane condensation. As we can see, both water flux and heat flux reduces significantly with the increase of the transmembrane pressure difference. The flux decline can be explained by several reasons. First, in this study increasing the pressure on the gas side is realised by adjusting the control valve at the outlet of the membrane module, which suggests reducing the gas stream flow rate. Even though it is not easy to experimentally measure the flow rate of the wet gas stream, it is expected that the gas stream flow rate reduces with increasing the transmembrane pressure. Therefore, less gas stream goes to and contacts with the membrane module, leading to a lower water flux and heat flux at higher transmembrane pressure. Second, vapor condensation is more likely to occur on the gas side at higher transmembrane pressure. This will increase the mass transfer resistance, resulting in the low mass transfer rate [15,32].

In addition, the water vapor content (i.e. humidity) and specific enthalpy of the gas stream reduce with the rise in transmembrane pressure (Fig. 11). This implies that less water vapor and heat go to the membrane module even though the air flow rate and temperature do not change. Therefore, higher pressure on the gas side results in lower water flux and heat flux across the membrane condenser.

However, reduced fluxes are not necessarily associated with recovery reduction. Fig. 12 presents the water recovery and heat recovery as a function of the transmembrane pressure difference. It seems that water recovery and heat recovery do not change a lot with the increase of the transmembrane pressure difference, particularly for the water recovery. This is reasonable since the

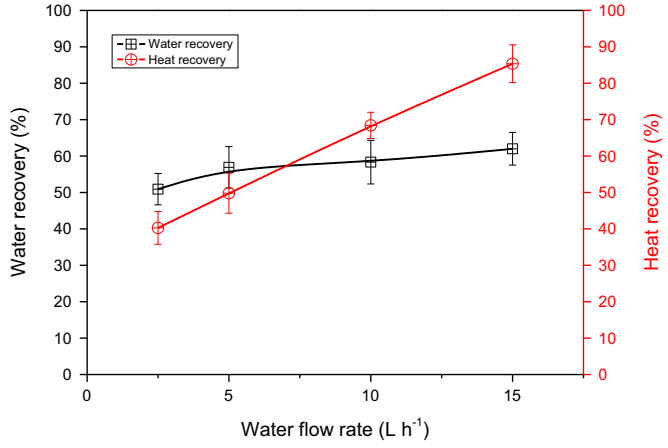


**Fig. 9.** Effect of water flow rate on water and heat recoveries across the membrane. Experimental conditions: water vapor saturated air as the gas stream; gas mixture temperature 77 °C; air flow rate 3 L/min; liquid side gauge pressure 0; gas side gauge pressure 0.04 MPa; effective membrane area 0.0021 $m^2$.

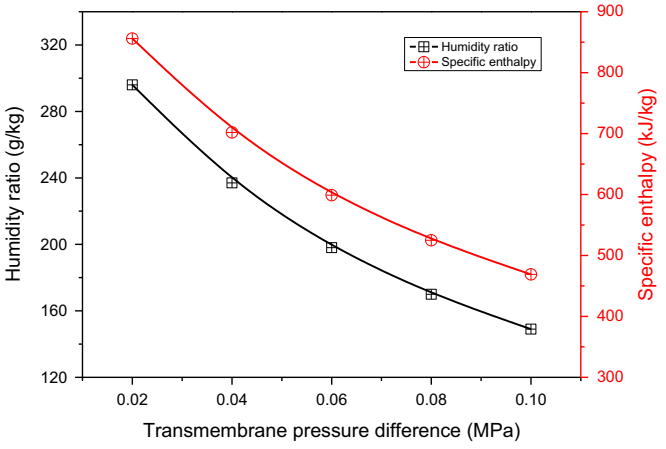


**Fig. 11.** Humidity ratio and specific enthalpy of the gas stream as a function of transmembrane pressure difference. Simulation data is obtained at the experimental temperature 75 °C for air by the Vaisala humidity calculator (version 3.0).

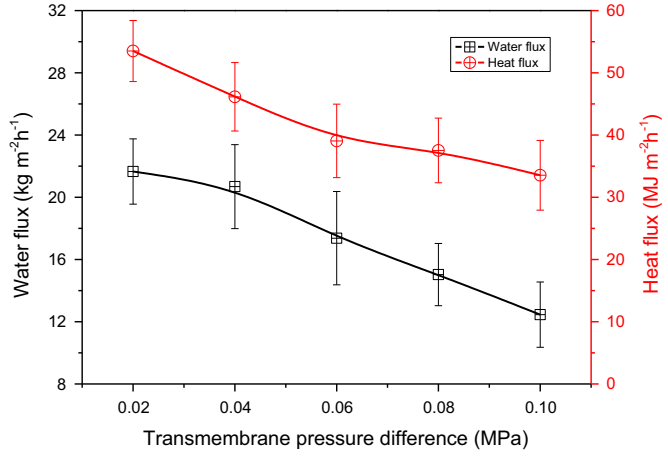


**Fig. 10.** Effect of transmembrane pressure difference on water and heat fluxes. Experimental conditions: water vapor saturated air as the gas stream; gas mixture temperature 75 °C; air flow rate 4 L/min; liquid flow rate 5 L/h; liquid side gauge pressure 0; effective membrane area 0.0021 $m^2$.

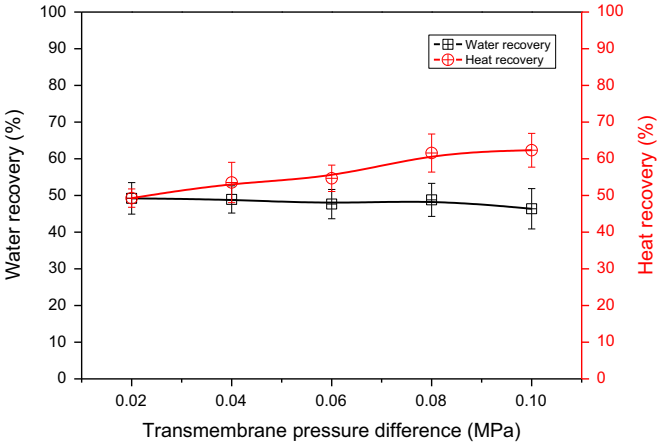


**Fig. 12.** Effect of transmembrane pressure difference on mass and heat recoveries. Experimental conditions: water vapor saturated air as the gas stream; gas mixture temperature 75 °C; air flow rate 4 L/min; liquid flow rate 5 L/h; liquid side gauge pressure 0; effective membrane area 0.0021 $m^2$.

water vapor and specific enthalpy in the gas stream reduce with the increase of the transmembrane pressure difference as shown in Fig. 11.

In the experiments, it was observed that gas bubbles occurred on the water side when the gas side pressure was increased to 0.08 MPa. It means that gas is forced from the gas side into the liquid side under the high pressure. The mass transfer mechanism may change when the gas goes across the membrane into the liquid. After the transmembrane pressure increases up to 0.08 MPa, however, the mass flux does not change irregularly as shown in Fig. 10. It suggests that the mass flux mainly determined by the inlet gas stream humidity (Fig. 11) rather than the transfer mechanism.

### 4.4. Effect of inlet gas temperature

Fig. 13 describes the effect of gas stream temperature on the mass and heat fluxes across the membrane. We can see that the inlet gas steam temperature has an important effect on the water flux and heat flux. With the rise in gas stream temperature, water flux and heat flux across the membrane increase significantly. For example, the water flux increases from 2 to 15 kg/m$^2$ h and the heat flux rises from 6 to 45 MJ/m$^2$ h when the inlet gas temperature varies from 45 °C to 85 °C. Compared with the water flux in a similar study [6], it is found that the recovered water flux is much higher in our study. It is likely caused by the coolant temperature difference. In the current study, the coolant water temperature is maintained stable with a cooling system. Therefore, a larger temperature difference and thus driving force across the membrane result in higher water flux.

The correlation between fluxes and temperature in Fig. 13 can be explained by several reasons. On one hand, the higher water flux may be caused by the higher water vapor content and higher specific enthalpy in the gas stream at higher temperature. On the other hand, the higher driving force resulted from the higher water vapor partial pressure on the gas side at higher temperature leads to the higher mass flux. Additionally, higher mass and heat transfer coefficients at higher temperature also facilitates the mass and heat transfer to some extent.

Fig. 14 shows the water recovery and heat recovery with the increase of the inlet gas temperature. It can be seen that water recovery increases obviously from 20% to 56% when the gas stream temperature increases from 45 °C to 85 °C. This change is in agreement with the increase in water flux. However, the heat recovery change with the gas temperature change shows an interesting trend.

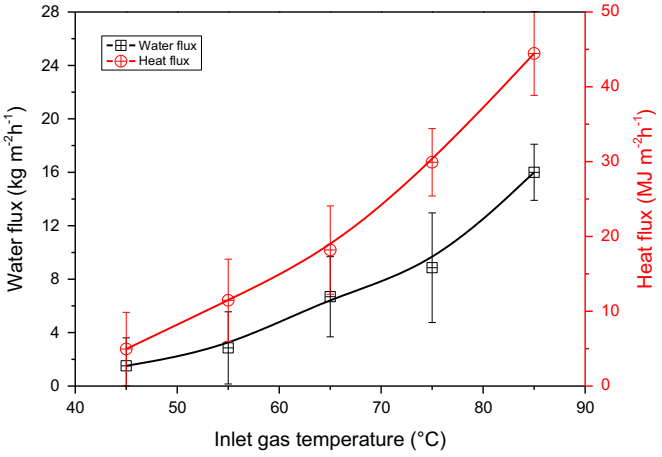


**Fig. 13.** Effect of gas mixture temperature on mass and heat fluxes across the membrane. Experimental conditions: water vapor saturated air as the gas stream; air flow rate 2 L/min; liquid water flow rate 5 L/h; liquid side gauge pressure 0; gas side gauge pressure 0.04 MPa; effective membrane area 0.0021 m$^2$.

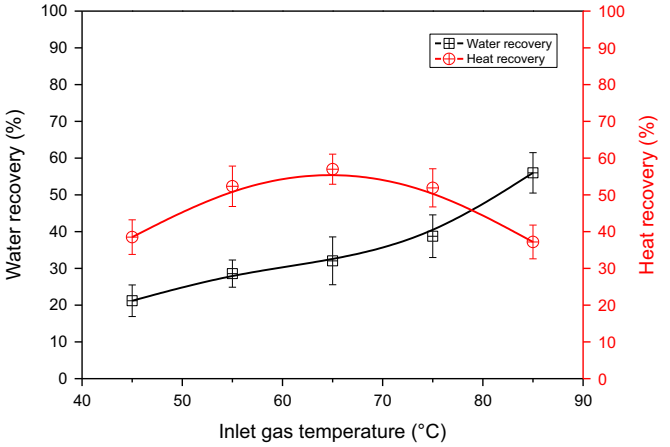


**Fig. 14.** Effect of gas mixture temperature on water and heat recoveries across the membrane. Experimental conditions: water vapor saturated air as the gas stream; air flow rate 2 L/min; liquid water flow rate 5 L/h; liquid side gauge pressure 0; gas side gauge pressure 0.04 MPa; effective membrane area 0.0021 m$^2$.

Heat recovery increases from 38% to 58% and then declines to 37% in the gas temperature change range. As we know, both heat flux and enthalpy of the inlet gas stream increase with the rise in temperature. Thus, heat recovery rises if the measured heat flux increases faster than the enthalpy change of the gas with temperature. However, when the inlet gas stream temperature (enthalpy) is so high that the transport membrane condenser cannot effectively transfer the heat across the membrane, the outlet gas stream temperature (enthalpy) will be high, which was observed in the experiments. As a result, lower heat recovery can be found in Fig. 14 at higher inlet gas temperature.

From Figs. 6–14, it can be seen that in most cases the water and heat fluxes and recoveries are not proportional. In addition to the above explanations from the point of review of fluid properties (e.g. the flow rate, temperature, humidity and enthalpy), it may also be explained by the difference between mass transfer and heat transfer. In the condensation process, mass transfer is determined by the temperature difference across the membrane and the membrane properties (e.g. membrane structure and thickness). Heat transfer is governed by the overall thermal conductivity (including those of the boundary layer and membrane) and convective heat flow (which is proportional to the mass transfer). Thus, the water and heat fluxes and recoveries are not always proportional in this study.

### 4.5. Mass and heat transfer mechanisms

The mass transfer mechanism in this study might be complex. It can be dominated by capillary condensation in the membrane pore (Fig. 2A) or condensation first and then diffusion (i.e. convective flow) (Fig. 2B) as explained in Section 2. According to the calculated Knudsen number, when a membrane pore size is smaller than 100 nm, Knudsen diffusion dominates the mass transfer in the process [15]. Since the pore size of the used membrane is on nanoscale, Knudsen diffusion may be the transfer mechanism. However, if the diffusion solute is not water vapor but liquid water (namely, condensation occurs on the gas side), the mass transfer mechanism will be different. In addition, the transmembrane pressure difference and water vapor partial pressure difference across the membrane also affect the mass transfer. Systematic investigation on the mass transfer mechanism is of great importance in membrane condensation for water and heat recovery, and it will be present in our future study.

Vapor condensation on the gas side is likely to be unavoidable due to the temperature drop along and cross the membrane, which will reduce the mass transfer and water recovery [15,32].

However, it might not significantly affect the heat transfer/recovery as the released latent via condensation can still go across the membrane by thermal conduction [33]. Heat transfer in the membrane condenser includes both convective heat associated with the mass transfer and conductive heat across the membrane. Therefore, heat recovery can be improved by increasing the mass transfer rate and/or selecting the thin membrane with high thermal conductivity [34]. In the future, the performances of using membranes with different thicknesses and conductivities should also be studied and compared.

## 5. Conclusions

In this study, we employ a tubular ceramic membrane as the condenser for simultaneous water and heat recovery from gaseous streams. The effects of some important operational parameters (e.g. gas flow rate, coolant flow rate, transmembrane pressure and inlet gas temperature) on the process performance in terms of mass and heat transfer across the membrane are systematically studied.

Experimental results show that mass and heat transfer rates across the membrane can be enhanced by increasing the gas flow rate, water flow rate and the temperature of the inlet gas stream. The water and heat recovery can be improved by lowering the gas flow rate or increasing the coolant flow rate. Increasing the transmembrane pressure difference decreases the mass and heat transfer mainly due to the reduced inlet gas humidity, enthalpy and flow rate. However, water and heat recovery does not change a lot with the change in transmembrane pressure. 20–60% water recovery and 33–85% heat recovery are achievable when using cold water as the coolant. The corresponding recoveries may become lower when the coolant temperature is increased. The mass transfer mechanism in membrane condensation can be very complicated and needs further exploration. These findings offer significant implications in using membrane condensers for water and heat recovery from gas streams with high moisture.

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