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Performance evaluation of water vapor and air recovery from flue gas in drying process using vacuum membrane vapor separation

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ABSTRACT

Membrane vapor separation has been a promising technology for both the recovery of water vapor and retentate air, including sensible heat. In this paper, to investigate the impact of operational parameters on the efficiency of water vapor recovery and air recirculation for sensible heat recycling, a lab-scale test was performed under various operating conditions using a non-porous polymeric membrane. From the results, by increasing the relative humidity, the amount of water vapor recovered significantly increased, though the recovery efficiency slightly decreased. The recirculation ratio related to sensible heat recovery did not change. The water recovery efficiency and recirculation rate were found to be significantly affected by changes in the feed flow. The recovery efficiency of water vapor was enhanced with a decrease in the feed flow rate, whereas the air recirculation ratio decreased due to a trade-off between permeability and selectivity. In terms of partial pressure on membranes, the separation performance was further changed by depressurization than compression. Overall, the decompression method was found to be more efficient when a partial pressure was supplied on the membrane surface.

Keywords: Membrane vapor separation; Air recirculation; Drying process; Flue gas; Energy recovery

1. Introduction

Interest in membrane water vapor separation is increasing due to advantages such as energy efficiency, simplicity, low cost, no phase conversion, and small footprint [1–3]. Recently, extensive research efforts have been carried out on the gas separation of water vapor and air. To date, water vapor separation technology using a membrane has been applied in isothermal processes such as air conditioning [4], flue gas dehydration [5,6], and steam recovery [6–8]. In terms of water vapor recovery, membrane processes have been utilized to produce renewable energy through the recovery of latent and sensible heat in wasted steam [9,10]. In this process, permeate gas, including the latent heat of vapor, is available as a renewable energy via a heat exchanger [11,12], though there has yet to be a study and utilization of retentate gas in this manner. Retentate gas could be also utilized as a renewable energy by the recirculation of air, due to its inclusion of sensible heat.

For example, the recirculation of retentate gas for recovery sensible heat could be applied during the drying process. The drying process has been considered the highest energy-consuming process. Numerous scientists and technicians have agonized over ways to save this energy [8]. Researchers have primarily focused on recovering the latent heat in the vapor. However, in attempts to maximize the energy efficiency, membrane processes have made it possible to also recover the sensible heat. During dehydration, saturated water vapor at high temperature(energy) will be generated for recovering the moisture of the dried product. When the hot and humid air from the drying process penetrates and passes through the membrane, the water vapor could be selectively sieved out, leaving only air (O_2, N_2) that includes sensible heat. In this way, sensible heat of retentate gas could be recycled via recirculation to the feed. This

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proposed process is similar to other membrane processes [6,7], except it includes a dryer process in order to capture hot and humid air as the air recirculates. Overall, the operational energy can be reduced by applying a membrane water vapor separation to drying process. However, further studies are required as follows.

Researchers have investigated various approaches to improve water vapor permeance and selectivity by preparing different membranes. An et al. [13] used a microporous Engelhard titanosilicate-4 incorporated thin film nanocomposite combined with a polymer membrane for water vapor separation. In another study, a polyethersulfone-based thin film composite membrane was prepared using aqueous monomers to enhance the permeability and selectivity [14,15]. A summarization of water vapor permeability and vapor/nitrogen selectivity for various polymer membranes can be found in Refs. [6,16,17]. Notably, only a few studies have investigated the effect of operating conditions on vapor recovery in membrane separation processes. In membrane gas separation processes, the effect of temperature on separation performance is relatively well known, whereas the effect of relative humidity, feed flow and pressure is not. In general, with increases in the temperature and pressure, the permeability improves, while the selectivity deteriorates under fixed feed flow conditions [18]. However, even if the feed flows are identical, the moisture content changes depending on the relative humidity. Therefore, an experimental study investigating water vapor recovery according to operational conditions such as partial pressure, relative humidity, and feed flow is needed.

In this paper, for the successful application of these hybrid process, both phenomena concerning vapor recovery and air recovery for sensible heat recovery are investigated using vacuum membrane vapor separation system. This study focuses on the evaluating the performance according to operational parameters including partial pressure, temperature, relative humidity, and feed flow. Finally, in terms of potential for scale-up,operational parameters are discussed.

2. Materials and methods

2.1. Commercial vapor separation membrane module

A commercial hollow-fiber membrane (MMDHF, Airrane, Korea) was applied for use in vapor recovery from humid air. The same commercial membrane module was used in a previous study [19]. The commercial membrane was consisted of polysulfone (PSf) coated with polydimethylsiloxane (PDMS). The commercial module included 900 ea hollow fibers and an effective area of 0.65 m^2. The O_2 permeance of the membrane was 100 GPU, and the O_2/N_2 selectivity was estimated to be 2.2. The characteristics of the membrane module were subsequently investigated using scanning electron microscopy (FE-SEM S-4700, Hitachi, Japan) and Fourier-transform infrared spectroscopy (Perkinelmer, USA).

2.2. Lab-scale membrane separation system operation

A lab-scale membrane separation system was set up to determine the performance based on changes in operating conditions. The system consisted of an air regulator, mass flow controller (MFC), 1st heater, water tank, 2nd heater, 3rd heater, hygrometer, membrane module, mass flow meter (MFM), and vacuum pump (Fig. 1).

The feed flows from outside of the membrane to the inside. The role of each apparatus and system operation procedure are as follows. To apply a driving force, compressed air less than 1 bar was transported to the module through the MFC, 1st heater, water tank, and 3rd heater. The flow of compressed air was adjusted by the MFC from 0 LPM to 200 LPM. Vapor at the desired temperature and relative humidity was generated using a 3-step heating process: the 1st heater and 2nd heater generated saturated water vapor at the desired humidity and the temperature was then adjusted using the 3rd heater. Gas passing through the membrane module was separated into two parts, dry air and vapor, using a vacuum pump, which was more energy efficient than using a compressor [20]. During these experiments, the relative humidity and temperature in the inflow and outflow of the membrane module were automatically recorded using a laptop.

2.3. Experimental conditions for performance evaluation

The experimental conditions for evaluating the membrane performance are listed in Table 1. To investigate the effect of operational conditions on recovering vapor and recirculating air, separation tests were performed while varying the relative humidity, feed flow, and partial pressure.

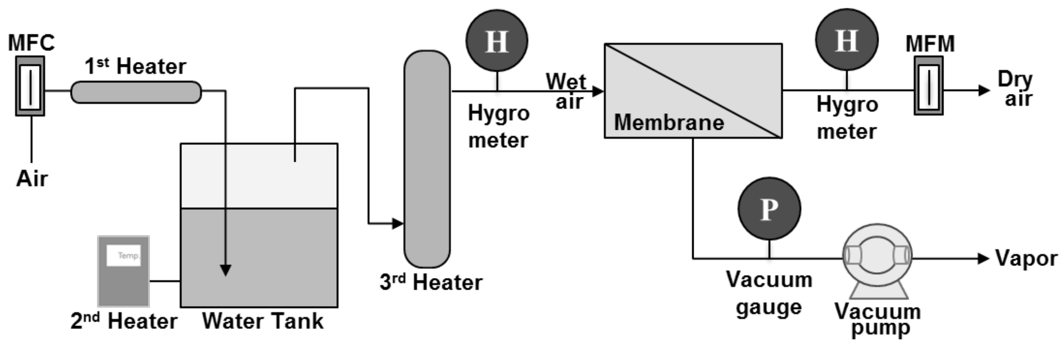

Fig. 1. Schematic diagram of the lab-scale membrane vapor separation system.

Table 1
Experimental conditions for evaluating membrane performances

Operational parameters	Experimental conditions			
	Relative humidity	Feed flow	Inlet gauge pressure	Permeate gauge pressure
Relative humidity (%)	70, 80, 90, 95	80	80	80
Feed flow (L/min)	30	20, 30, 40, 50	30	30
Inlet gauge pressure (bar)	1	1	0.4, 0.6, 0.8, 1	1
Permeate gauge pressure (bar)	0.9	0.9	0.9	0.6, 0.7, 0.8, 0.9

In the lab-scale separation system, results for the relative humidity and temperature at the inflow and outflow of the membrane module were recorded in real-time. From these data, the recovered water, vapor recovery efficiency, and recirculation of air were estimated using the following equations.

$$AH = \left(-4\times10^{-14}\times T^6\right)+\left(2\times10^{-11}\times T^5\right)+\left(10^{-9}\times T^4\right) +\left(2\times10^{-7}\times T^3\right)+\left(9\times10^{-6}\times T^2\right)+\left(4\times10^{-4}\times T\right)+0.0035 \quad (1)$$

where AH is the absolute humidity (g vapor/m^3 air) under constant temperature conditions, and T is the gas temperature (°C) of the membrane module inflow or outflow.

$$M_{inflow} = AH_{inflow}\times1000\times RH_{inflow} \quad (2)$$

where M_{inflow} is the flow of vapor in the feed (g vapor/m^3 air), AH_{inflow} is the absolute humidity of the feed flow, and RH_{inflow} is the relative humidity of the feed flow (%).

$$M_{outflow} = AH_{outflow}\times1000\times RH_{outflow} \quad (3)$$

where $M_{outflow}$ is the flow of vapor on the retentate side (g vapor/m^3 air), $AH_{outflow}$ is the absolute humidity of the retentate flow, and $RH_{outflow}$ is the relative humidity of the retentate flow (%).

$$MQ_{inflow} = M_{inflow}\times Q_{inflow} \quad (4)$$

where MQ_{inflow} is the amount of vapor injected into the feed flow (g vapor/min), and Q_{inflow} is the feed flow (L/min).

$$MQ_{outflow} = M_{outflow}\times Q_{outflow} \quad (5)$$

where $MQ_{outflow}$ is the amount of vapor not penetrating into the membrane (g vapor/min), and $Q_{outflow}$ is the retentate flow (L/min).

$$\Delta MQ = MQ_{inflow} - MQ_{outflow} \quad (6)$$

where ΔMQ is the amount of vapor recoverd (g vapor/min).

$$MQ_{ratio} = \Delta MQ / MQ_{inflow} \quad (7)$$

where MQ_{ratio} is the vapor recovery efficiency (%).

$$R_{air} = Q_{inflow} / Q_{outflow} \quad (8)$$

where R_{air} is the recirculation ratio of air (%).

3. Results and discussion

3.1. Characteristics of commercial membrane

Characteristics of the commercial membrane were investigated using SEM (Fig. 2) and FT-IR (Fig. 3). The external diameter and an internal diameter were determined to be approximately 960 and 730 µm, respectively. The presence of macro-voids was confirmed by observing the cross-sectional view of the membrane; no cracks or defects were observed on the outer surface of the membrane. PSf membranes are known to have high selectivity but low permeance, whereas PDMS membranes have a high permeance but low selectivity [21]. The IR peak associated with PSf was presented as sulfone group peak (1147, 1294 and 1324 cm^{-1}) and stretching of carbon-carbon bonds (1487 and 1585 cm^{-1}) [22]. The IR peak regarding PDMS was presented at 804 cm^{-1} (Si-CH_3), 1013 to 1101 cm^{-1} (Si-O-Si), 1241 cm^{-1} (Si-CH_3), and 2871 cm^{-1} (asymmetric CH_3 stretching in Si-CH_3) [23].

3.2. Effect of relative humidity on separation performance

The amount of water vapor in flue gas changed based on the relative humidity at identical temperatures, and affected the separation performance (Figs. 4 and 5). The theoretical amount of water vapor increased to 302.95, 372.1, 452.5, and 497.7 g vapor/m^3 air, respectively, when the relative humidity was increased to 70, 80, 90, and 95% RH at 80°C. The improved relative humidity caused an increase in both the permeate and retentate vapor. As the relative humidity was increased from 70% to 95%, the permeate and retentate vapor increased from 4.99 g/min to 7.08 g/min, and from 1.18 g/min to 1.33 g/min, respectively. Notably, the permeate vapor increased more in comparison with the retentate vapor when the relative humidity was increased. As a result, the recovery efficiency of the vapor slightly improved. Previously, Zhao et al. [8] and Hu et al. [24] studied vapor recovery from flue gas using a hydrophobic and hydrophilic porous membrane, respectively. In their studies, the relative humidity had less effect on the water vapor recovery than parameters such as temperature, pressure, and feed flux.

Recirculation air was measured to be about 80.5% under all conditions. The recirculation ratio of air was relatively constant because the air content in the feed was not affected by changes in the relative humidity. Even though the water vapor in the feed flow significantly varied according to the relative humidity, the air content in the feed remained constant. In other words, the retention time for the feed flow per membrane area was identical, but the amount of water

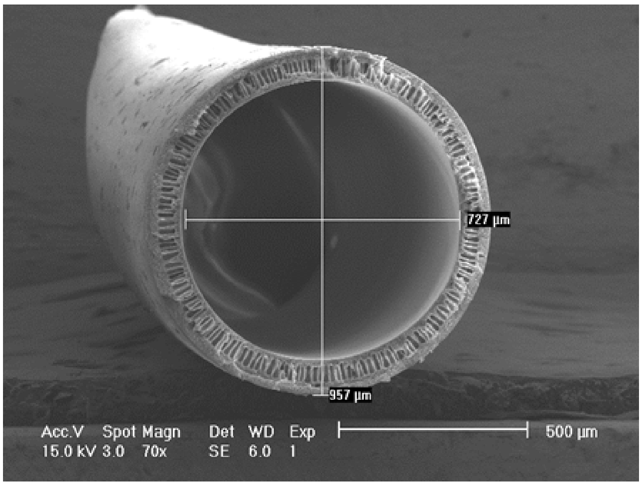

Fig. 2. SEM image of hollow fiber in commercial membrane module.

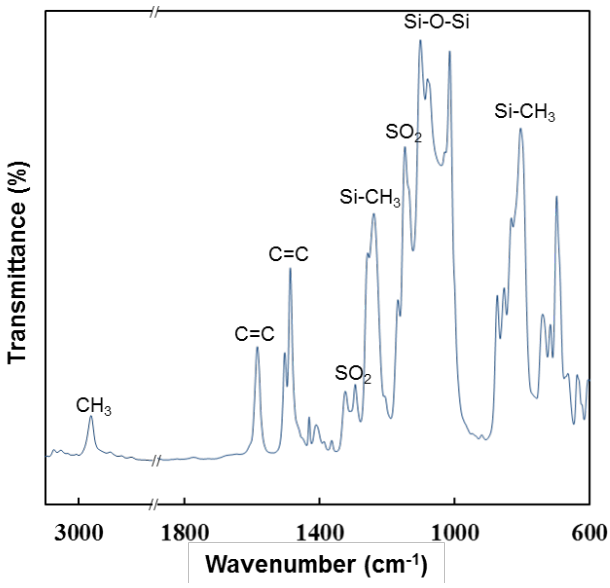

Fig. 3. FT-IR spectrum of commercial hollow fiber membrane.

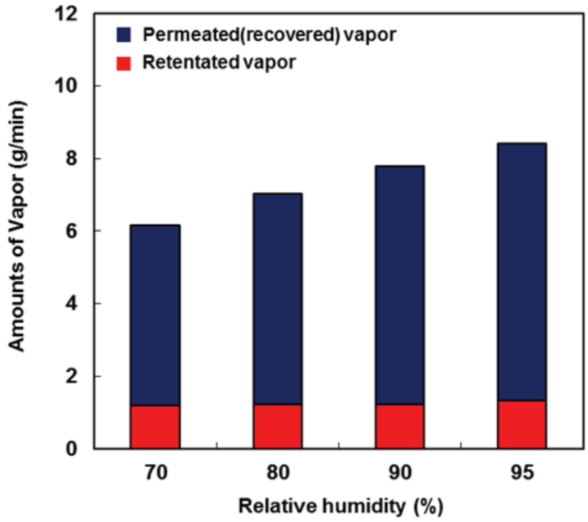

Fig. 4. Permeate and retentate vapor with respect to relative humidity. Operational conditions: temperature, 80°C; feed flow, 30 L/min; inlet gauge pressure, 1 bar; permeate gauge pressure, 0.9 bar; and effective membrane area, 0.65 m^2.

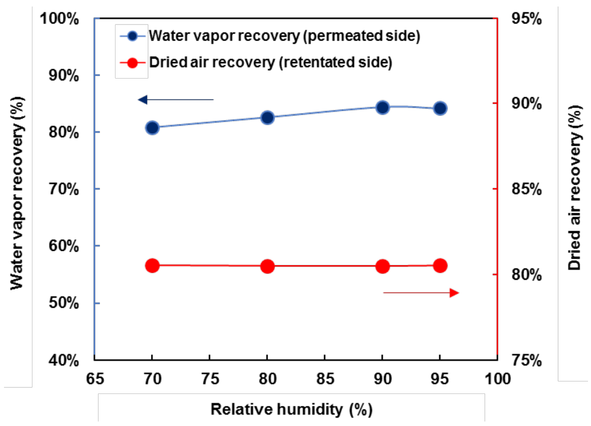

Fig. 5. Recovery of water vapor and air based on permeate side pressure. Operational conditions: temperature, 80°C; feed flow, 30 L/min; relative humidity, 80%; inlet gauge pressure, 1 bar; and effective membrane area, 0.65 m^2.

vapor in contact with the membrane surface was different. Therefore, by increasing the relative humidity, the amount of water vapor in the feed increased and the amount of vapor recovered proportionally improved.

3.3. Effect of feed flow on separation performance

The effect of feed flow on retention time is a major parameter because membrane gas separation is based on the solubility and permeability on membrane surface. Here, the separation performance was investigated at feed flows of 20, 30, 40, and 50 L/min (Figs. 6 and 7). By increasing the feed flow from 20 L/min to 50 L/min, the permeate and retentate vapor increased to 8.71 L/min from 4.02 g/min, and to 2.90 L/min from 0.62 L/min, respectively. Note that even though the permeability improved due to the increase of vapor quantity in contact with the membrane surface,the increase of feed vapor quantity acted as a trigger for reducing the retention time of water vapor on the membrane surface. Since the increase of the flow quantity for a fixed module size indicated an increase in the flow velocity, the time needed for each water molecule to contact the membrane surface decreased. For this reason, the selectivity also decreased. As a result, the retentate vapor increased more than the permeate vapor with increases in the feed flow; hence, the recovery of water vapor deteriorated in spite of the increase in water vapor recovered. Brunetti et al. introduced the factor, feed flow divided by membrane area, as an intensive parameter that can be used to calculate the area of the membrane at defined feed flow for ensuring the best performance of the system [25].

In contrast to the water vapor recovery, for air recovery, a growing trend was observed when the feed flow was

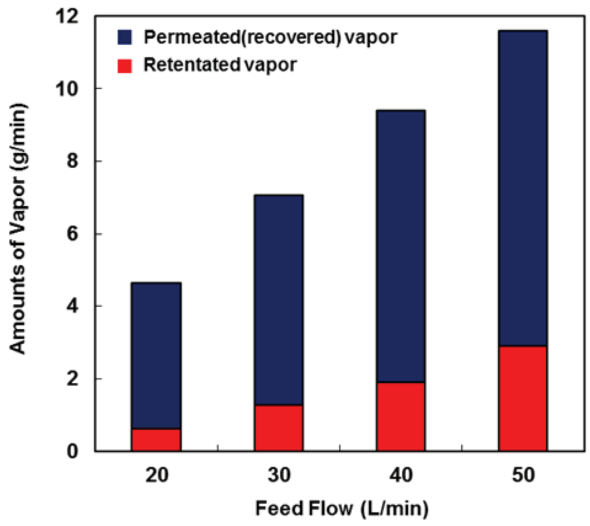

Fig. 6. Permeate and retentate vapor with respect to feed flow. Operational conditions: temperature, 80°C; relative humidity, 80%; inlet gauge pressure, 1 bar; permeate gauge pressure, 0.9 bar; and effective membrane area, 0.65 m^2.

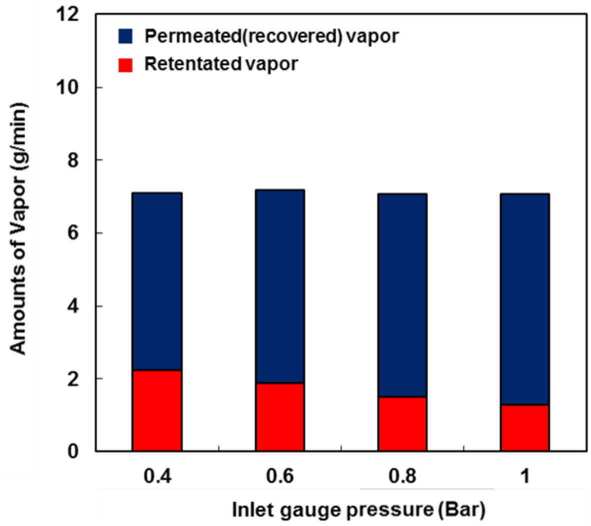

Fig. 8. Permeate and retentate vapor with respect to the inlet gauge pressure. Operational conditions: temperature, 80°C; feed flow, 30 L/min; relative humidity, 80%; permeate gauge pressure, 0.9 bar; and effective membrane area, 0.65 m^2.

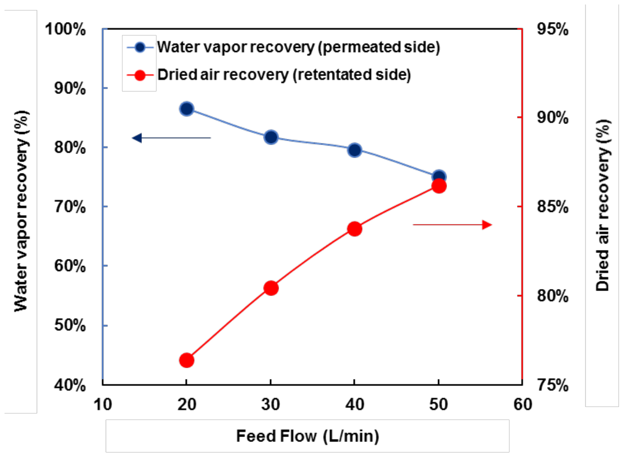

Fig. 7. Recovery of water vapor and air with respect to feed flow. Operational conditions: temperature 80°C; relative humidity, 80%; inlet gauge pressure, 1 bar; permeate gauge pressure, 0.9 bar; and effective membrane area, 0.65 m^2.

increased (Fig. 8). With an increase of feed flow from 20 L/min to 50 L/min, a minor increase from 4.8 L/min to 6.9 L/min was observed in the permeate flow. The selectivity of air (O_2 and N_2) was dramatically higher than for water vapor (H_2O) at the PDMS membrane [26]. Almost no air penetrated the membrane in spite of the increased air in contact with the membrane. With the increase of feed flow, however, the air recovery improved while the water recovery decreased.

3.4. Effect of partial pressure on separation performances

In membrane gas separation processes, the gas mixture separates based on the solution-diffusion mechanism related to the partial pressure between the inlet and permeate sides [27]. To apply a partial pressure on the membrane, the feed was simultaneously pressurized at the inlet side and depressurized at the outlet side using a vacuum pump. The increase in inlet pressure increased the permeate vapor and water recovery, but led to a decrease in the air recovery (Figs. 8 and 9). When the inlet pressure was increased, the permeate vapor increased and the retentate vapor decreased (Fig. 8). Although a major parameter affecting the permeability was the material of fabricated membrane, due to principles of gas membrane separation based on solution-diffusion theory, the pressure also substantially affected the permeability due by applying the driving force. The permeance of both the vapor and air subsequently increased. For this reason, the water vapor recovery increased and dried air recovery decreased (Fig. 9). Numerically, water recovery increased by pressure with increases in the inlet pressure in membrane condenser [28]. The air recovery increased with a decrease in the inlet pressure, with more than 90% of the air recovered at 0.4 bar.

Figs. 10 and 11 show the effects of depressurization on the separation performance. The amount of permeate vapor and the recovery efficiency dramatically improved at higher vacuum pressures. The trends for the separation performance were the same as for when an inlet pressure was applied. However, the rate of increase or decrease was higher when the pressure was depressurized than when pressurized. When the permeate gauge was depressurized to 0.8 from 0.6 bar, the amount of recovery and efficiency of water vapor at the permeate side increased about 131% to 5.25 g/min from 4.02 g/min and to 75.5% from 56.7%, respectively. When the inlet pressure was increased from 0.4 bar to 0.6 bar, the amount of recovery and efficiency of water vapor increased about 118% to 5.28 g/min from 4.46 g/min and to 73.6% from 62.2%, respectively. The increase of pressure is likely to incur an increase in the operational cost because the pressure is related to energy consumption; however, a higher pressure enables more water vapor to be recovered. From this point of view, decompression appears

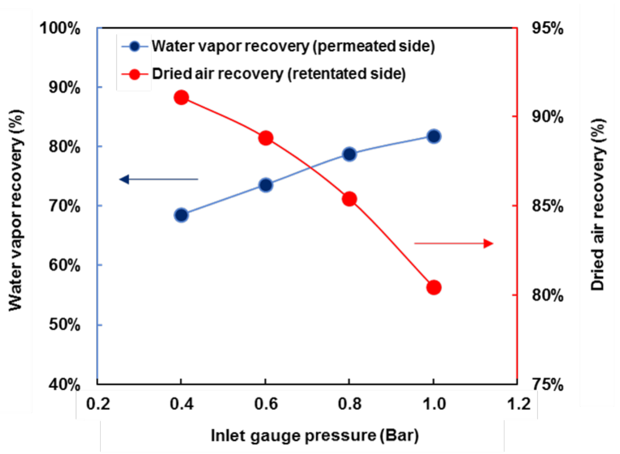

Fig. 9. Recovery of water vapor and air based on inlet gauge pressure. Operational conditions: temperature, 80°C; feed flow, 30 L/min; relative humidity, 80%; permeate gauge pressure, 0.9 bar; and effective membrane area, 0.65 m^2.

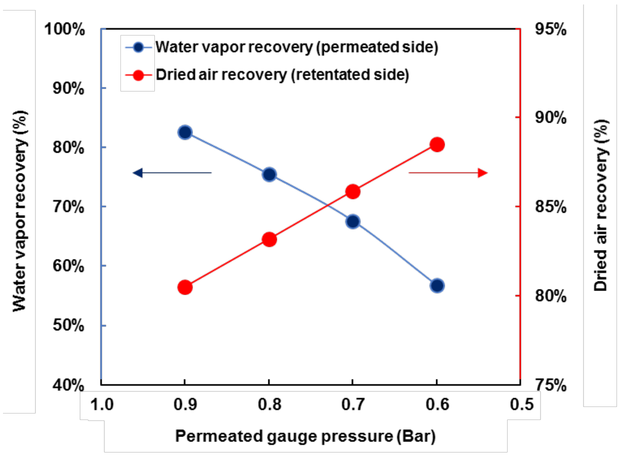

Fig. 11. Recovery of water vapor and air based on permeate side pressure. Operational conditions: temperature, 80°C; feed flow, 30 L/min; relative humidity, 80%; inlet gauge pressure, 1 bar; and effective membrane area, 0.65 m^2.

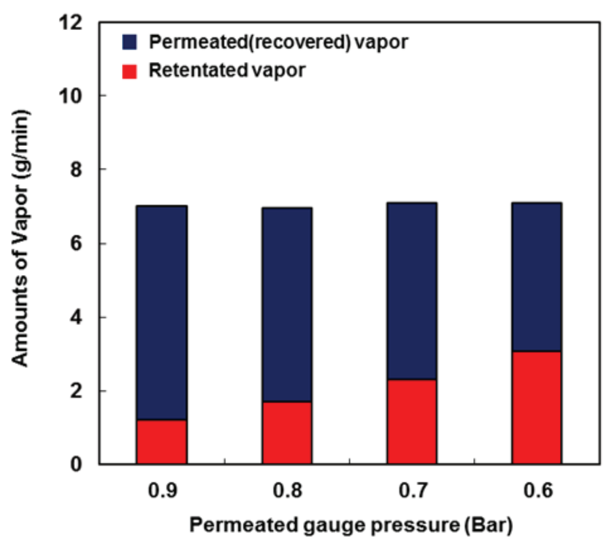

Fig. 10. Permeate and retentate vapor with respect to permeate side pressure. Operational conditions: temperature, 80°C; feed flow, 30 L/min; relative humidity, 80%; inlet gauge pressure, 1 bar; and effective membrane area, 0.65 m^2.

Table 2
Correlation between the membrane performance and operational parameters

Performances	Operational parameters			
	Relative humidity	Feed flow	Inlet gauge pressure	Permeate gauge pressure
Amounts of permeate vapor	O	O	O	O
Vapor recovery efficiency	×	Δ	O	O
Air recovery efficiency	×	Δ	Δ	Δ

O: Variation within more than 15%, Δ: Variation between 15% to 5%, ×: Variation within less than 5%.

to be the more efficient operation option. A similar parametric study regarding energy consumption in membrane process shows compression consumes more energy than the vacuum pumping [29]. For the minimum energy consumption, they introduced a method of using compression and vacuum at the same time. It was calculated that the energy required decrease down to 0.75 MJ kg^{-1} of CO_2 separation, which is lower than absorption requirements.

3.5. Technical considerations for operational parameters prior to scale-up

To identify major parameters affecting membrane performances from among operational conditions such as relative humidity, feed flow, and partial pressure, lab-scale experiments were performed. From the experimental results, correlations between membrane performances and operational parameters are summarized in Table 2.

The relative humidity affected the saturated water vapor, as the amount of vapor recovered increased with the increase of relative humidity in the feed, though the change in recovery efficiencies were negligible. The feed flow affected the retention time of vapor on the membrane surface. When the temperature was increased vapor, the vapor recovered increased since the feed contained a higher amounts of vapor than at low temperature, at the same relative humidity. When the flow rate was decreased, i.e., velocity reduction, the water vapor remained on the membrane surface for a longer time. Hence, the vapor recovery efficiency significantly improved. The amount of vapor recovered increased as the feed flow was reduced due to the corresponding increase in the vapor inflow per unit time. This increase was minimal, however, compared to parameters such as temperature and relative humidity. The partial pressure was a function of the driving force for mixed gas separation. Therefore, it is only one of the primary parameters affecting the amount of vapor recovered and the recovery efficiency, but it is a minor parameter in terms of air recirculation.

4. Conclusions

This study was performed at laboratory-scale in order to confirm membrane separation performances such as simultaneous water vapor recovery and sensible heat recovery from humid air. To achieve these objectives, the experimental study was performed by applying a variety of operating parameters.

The relative humidity was found to be a minor factor affecting scale-up since the efficiencies of water recovery and heat recovery were negligibly affected by varying the relative humidity. The separation performances were clearly enhanced by increasing the vacuum pressure, though the increase was limited as increasing the vacuum pressure is related to the operational costs. More significantly, to improve the recovery efficiency, the feed flow should be reduced in order to increase the retention time per unit membrane area, or the effective membrane area should be extended.

These results highlight the potential for simultaneous water recovery and heat recovery in one process. Although this study is only first step in developing these concepts, further study will expand this research into the application of other membranes, cost analyses, model simulations, and other experimental studies prior to scale-up.

Acknowledgements

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References

[1] S.S. Madaeni, M.M.S. Badieh, V. Vatanpour, Effect of coating method on gas separation by PDMS/PES membrane, Polym. Eng. Sci., 53 (2013) 1878–1885.
[2] A.F. Ismail, T.D. Kusworo, A. Mustafa, Enhanced gas permeation performance of polyethersulfone mixed matrix hollow fiber membranes using novel Dynasylan Ameo silane agent, J. Membr. Sci., 319 (2008) 306–312.
[3] H. Yang, Z. Xu, M. Fan, R. Gupta, R.B. Slimane, A.E. Bland, I. Wright, Progress in carbon dioxide separation and capture: A review, J. Environ. Sci., 20 (2008) 14–27.
[4] J. Woods, Membrane processes for heating, ventilation, and air conditioning, Renew. Sust. Energ. Rev., 33 (2014) 290–304.
[5] H. Sijbesma, K. Nymeijer, R. van Marwijk, R. Heijboer, J. Potreck, M. Wessling, Flue gas dehydration using polymer membranes, J. Membr. Sci., 313 (2008) 263–276.
[6] B. Bolto, M. Hoang, Z. Xie, A review of water recovery by vapour permeation through membranes, Water Res., 46 (2012) 259–266.
[7] F. Macedonio, A. Brunetti, G. Barbieri, E. Drioli, Membrane condenser configurations for water recovery from waste gases, Sep. Purif. Technol., 181 (2017) 60–68.
[8] S. Zhao, S. Yan, D.K. Wang, Y. Wei, H. Qi, T. Wu, P.H.M. Feron, Simultaneous heat and water recovery from flue gas by membrane condensation: Experimental investigation, Appl. Therm. Eng., 113 (2017) 843–850.
[9] T.D. Bui, F. Chen, A. Nida, K.J. Chua, K.C. Ng, Experimental and modeling analysis of membrane-based air dehumidification, Sep. Purif. Technol., 144 (2015) 114–122.
[10] P. Scovazzo, A.J. Scovazzo, Isothermal dehumidification or gas drying using vacuum sweep dehumidification, Appl. Therm. Eng., 50 (2013) 225–233.
[11] M. Nasif, R. Al-Waked, G. Morrison, M. Behnia, Membrane heat exchanger in HVAC energy recovery systems, systems energy analysis, Energ. Buildings, 42 (2010) 1833–1840.
[12] M.S. Nasif, R. Al-Waked, Seasonal Weather Conditions Effect on Energy Consumption and CO_2 Emission for Air Conditioning Systems Coupled with Enthalpy Energy Recovery Heat Exchanger, APCBEE Procedia, 10 (2014) 42–48.
[13] X. An, P.G. Ingole, Won K. Choi, Hyung K. Lee, S.U. Hong, J.-D. Jeon, Enhancement of water vapor separation using ETS-4 incorporated thin film nanocomposite membranes prepared by interfacial polymerization, J. Membr. Sci., 531 (2017) 77–85.
[14] S.H. Yun, P.G. Ingole, K.H. Kim, W.K. Choi, J.H. Kim, H.K. Lee, Properties and performances of polymer composite membranes correlated with monomer and polydopamine for flue gas dehydration by water vapor permeation, Chem. Eng. J., 258 (2014) 348–356.
[15] P.G. Ingole, W.K. Choi, G.B. Lee, H.K. Lee, Thin-film-composite hollow-fiber membranes for water vapor separation, Desalination, 403 (2017) 12–23.
[16] B. Bolto, M. Hoang, S.R. Gray, Z. Xie, 9 - New generation vapour permeation membranes, in: Pervaporation, Vapour Permeation and Membrane Distillation, Woodhead Publishing, Oxford, 2015, pp. 247–273.
[17] S.J. Metz, W.J.C. van de Ven, J. Potreck, M.H.V. Mulder, M. Wessling, Transport of water vapor and inert gas mixtures through highly selective and highly permeable polymer membranes, J. Membr. Sci., 251 (2005) 29–41.
[18] M. Ostwal, J.M. Lau, C.J. Orme, F.F. Stewart, J.D. Way, The influence of temperature on the sorption and permeability of CO_2 in poly(fluoroalkoxyphosphazene) membranes, J. Membr. Sci., 344 (2009) 199–203.
[19] M.-S. Shin, Y.-W. Jeon, Effect of membrane selectivity and partial pressure on vapor recovery and sensible heat recovery in membrane processes, Energy Procedia, 136 (2017) 323–329.
[20] A. Brunetti, F. Scura, G. Barbieri, E. Drioli, Membrane technologies for CO_2 separation, J. Membr. Sci., 359 (2010) 115–125.
[21] Yadvika, Santosh, T.R. Sreekrishnan, S. Kohli, V. Rana, Enhancement of biogas production from solid substrates using different techniques––a review, Bioresour. Technol., 95 (2004) 1–10.
[22] M. Nadour, F. Boukraa, A. Ouradi, A. Benaboura, Effects of methylcellulose on the properties and morphology of polysulfone membranes prepared by phase inversion, Mater. Res., 20 (2017) 339–348.
[23] L. Jihoon, K. Jungwoo, K. Hyoungsub, B. Young Min, L. Kyeong-Hee, J.C. Hyoung, Effect of thermal treatment on the chemical resistance of polydimethylsiloxane for microfluidic devices, J. Micromech. Microeng., 23 (2013) 035007.
[24] H.W. Hu, G.H. Tang, D. Niu, Wettability modified nanoporous ceramic membrane for simultaneous residual heat and condensate recovery, Sci. Rep., 6 (2016) 27274.
[25] E. Drioli, S. Santoro, S. Simone, G. Barbieri, A. Brunetti, F. Macedonio, A. Figoli, ECTFE membrane preparation for recovery of humidified gas streams using membrane condenser, React. Funct. Polym., 79 (2014) 1–7.
[26] L.M. Robeson, The upper bound revisited, J. Membr. Sci., 320 (2008) 390–400.
[27] M.B. Rao, S. Sircar, Nanoporous carbon membranes for separation of gas mixtures by selective surface flow, J. Membr. Sci., 85 (1993) 253–264.
[28] F. Macedonio, A. Brunetti, G. Barbieri, E. Drioli, Membrane condenser as a new technology for water recovery from humidified "waste" gaseous streams, Ind. Eng. Chem. Res., 52 (2013) 1160–1167.
[29] R. Bounaceur, N. Lape, D. Roizard, C. Vallieres, E. Favre, Membrane processes for post-combustion carbon dioxide capture; a parametric study, Energy, 31 (2006) 2556–2570.