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Evaluation of the Potential for Dehumidification by Using Membranes for Energy Conservation

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ABSTRACT: *In general buildings such as offices and factories, air-conditioning systems comprise roughly one-third of the overall energy consumed, or even comprise half in some specific buildings, such as large shopping centers and industrial plants. Along with the promotion of energy conservation and carbon reduction policies in recent years, exploitation of energy conservation technologies in air-conditioning systems has gradually become the focus of all manufacturers. Simply applying condensation dehumidification is energy consuming because usually reheating is required. Alternatively, membrane dehumidification can drastically reduce energy consumption. This study evaluates the performance of hydrophilic polyvinyl alcohol (PVA) membrane dehumidification. PVA was coated onto a surface with favorable mechanical strength, chemical resistance, and thermal stability to create a composite membrane and altered the dehumidification effects of the membrane by changing the PVA concentrations in the aqueous solution. Findings showed that aqueous solution with a higher PVA concentration fabricated membranes with better dehumidification efficiency but associate with a reduction in air flow rate. By contrast, aqueous solution with a lower PVA concentration fabricated membranes with poorer dehumidification efficiency but with an improvement on air flow rate. Potential of the energy conservation for membrane-dehumidification is "availability" on the air-conditioning by the evaluation from this experiment.*

KEYWORDS: *Air-conditioning, Dehumidification, Membrane, PVA, Energy conservation*

1. INTRODUCTION

Amidst the rapid development of industry, business and information, air-conditioning system have become increasingly important for controlling the temperature and humidity of regional environments, no matter in residential/commercial environments or industrial manufacture (e.g., semiconductor manufacture, biomedical development or machine room heat dissipation).

On the other hand, air-conditioning and ventilation consume over 30% of the overall energy required for operation. The functions of air-conditioning systems mainly categories into cooling and dehumidifying. Among which dehumidifying consumes roughly 30% to 50% of the overall energy required for air-conditioning and therefore it is an influential factor on energy consumption of air-conditioning systems. Furthermore, dehumidification could even surpass cooling as the primary function of air-conditioning systems in specific environments, such as low-temperature, high-humidity environments during the spring season. To dehumidify these environments, the environment is cooled down and dehumidified, and then reheated using a same or larger amount of energy, causing double energy consumption. This highlights the necessity of developing new dehumidification technologies for independent humidifiers and/or air-conditioning systems while this new air-conditioning technology must aim at improving both living environments and the earth.

Membrane gas separation is the most direct separation method and it is also the most energy efficient gas separation method. Applying membranes into dehumidification technologies could significantly reduce the energy consumption for dehumidification. Reducing energy consumption not only reduces cost, it also contributes to energy conservation and carbon reduction. This study adopted a solution coating method to fabricate composite membranes and the feasibility of applying membranes for dehumidification purpose was evaluated. Highly hydrophilic polymers are relatively more compatible with water molecules. Thus, using highly hydrophilic polymers in membrane can selectively isolate water molecules and provides a possibility to remove water vapor from the permeate gas. The most commonly used highly hydrophilic polymers for membrane fabrication is polyvinyl alcohol (PVA) and chitosan and PVA was selected in this study. Gas flux is the most important indicator of the gas separation performance of membranes. Membranes must have high gas flux to prepare composite membrane. To prepare composite membrane, suitable base films are required, materials which have excellent mechanical strength, chemical resistance, thermal stability, and film-forming potential are required to fabricate the base films. The most commonly used highly hydrophilic polymers for fabricating base films are polysulfide (PSf), polyacrylonitrile (PAN), and polyvinylidene fluoride (PVDF). PVDF was selected for base films fabrication in this study. The composite membrane for dehumidification was fabricated by combining PVA with PVDF base film. The composite membrane was comprehensively evaluated to determine the feasibility of using membranes in dehumidification.

II. MEMBRANE FABRICATING AND TESTING

Fabricating the PVDF Base Film : Weigh and pour 352 g of N-Methyl-2-pyrrolidone (NMP) into a serum flask. Weigh and pour 16 g of PVDF powder into the serum flask. Use an electromagnetic stirrer to heat and blend the solution. Thereafter, weigh and pour another 16 g of PVDF powder into the serum flask every hour until a total of 48 g of PVDF powder is added. Fully blend and dissolve the solution at 90°C for 24 hours to form the casting solution (PVDF (12 wt%)+NMP (88 wt%)). Settle at ambient temperature for 24 hours to deaerate the solution. Use a stationary cutter (thickness fixed at 200 μm) and spread an appropriate amount of casting solution onto a non-woven cloth. Immediately soak the cloth in the first water tank to solidify the membrane. After 10 min, soak the PVDF membrane in the second water tank for 24 hours to engage in solvent replacement. Finally, dry the membrane in an oven for 24 hours.

Fabricating the PVA Solution

PVA (1 wt%) : Weigh and pour 99 g of distilled water into a serum flask. Weigh and pour 1 g of PVA powder into the flask. Use an electromagnetic stirrer to heat and blend the solution. Fully blend and dissolve the solution at 90°C for 24 hours to form the casting solution (PVA (1 wt%)+water (99 wt%)). Settle at ambient temperature for 24 hours to deaerate the solution.

PVA (2 wt%) : Weigh and pour 98 g of distilled water into a serum flask. Weigh and pour 2 g of PVA powder into the flask. Use an electromagnetic stirrer to heat and blend the solution. Fully blend and dissolve the solution at 90°C for 24 hours to form the casting solution (PVA (2 wt%)+water (98 wt%)). Settle at ambient temperature for 24 hours to deaerate the solution.

PVA (3 wt%) : Weigh and pour 97 g of distilled water into a serum flask. Weigh and pour 3 g of PVA powder into the flask. Use an electromagnetic stirrer to heat and blend the solution. Fully blend and dissolve the solution at 90°C for 24 hours to form the casting solution (PVA (3 wt%)+water (97 wt%)). Settle at ambient temperature for 24 hours to deaerate the solution.

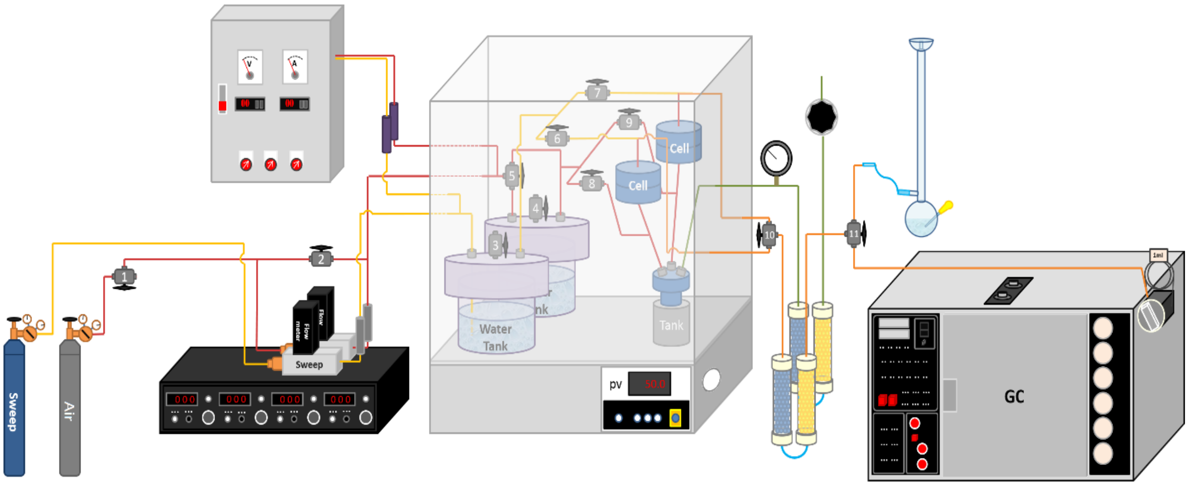
PVA (4 wt%) : Weigh and pour 96 g of distilled water into a serum flask. Weigh and pour 4 g of PVA powder into the flask. Use an electromagnetic stirrer to heat and blend the solution. Fully blend and dissolve the solution at 90°C for 24 hours to form the casting solution (PVA (4 wt%)+water (96 wt%)). Settle at ambient temperature for 24 hours to deaerate the solution.

PVA (5 wt%) : Weigh and pour 95 g of distilled water into a serum flask. Weigh and pour 5 g of PVA powder into the flask. Use an electromagnetic stirrer to heat and blend the solution. Fully blend and dissolve the solution at 90°C for 24 hours to form the casting solution (PVA (5 wt%)+water (95 wt%)). Settle at ambient temperature for 24 hours to deaerate the solution.

FABRICATING PVA COMPOSITE MEMBRANES : Use a stationary wire bar (thickness fixed at 28 μm) and spread an appropriate amount of PVA casting solution onto the PVDF base film. Immediately solidify the membrane in an oven at 60°C for 2 hours.

Performance Testing and Analysis for the PVA Membrane

Testing for Gas Permeation Unit and Water Vapor Permeate Concentration : The figure below shows the equipment setup for measuring Gas Permeation Unit. Gas chromatography (GC) was adopted to analyze the water vapor concentration in the gas.



Operating Procedures：

Mounting the membrane : Remove the cells with a No. 11 wrench. The cells contain two stainless steel disks and O-rings. One with large pores than the other. Their function is to support the membrane. The size of the membrane sample must be consistent with the size of the disks and larger than the O-rings. The order of placement is the disk with the large pores, the disk with the smaller pores, the membrane sample and then the O-ring.

Adjusting pressure : Before administering intake pressure, close off valve 8 and valve 9 and open valve 4. Adjust valve 1 to the desired gas type (air) and open the secondary valve to the maximum. Open the valve of the gas canister to administer the gas. Adjust the valve on the gas canister slowly. Wait until valve 4 begins to discharge gas slightly, then close off valve 4 and open valve 8 and valve 9. Once gas begins to discharge from the secondary valve, adjust the secondary valve clockwise until no further gas discharge and check whether the pressure monitor shows the required pressure value (1 atm). If the required pressure has not been reached, rotate the valve on the gas canister to release more gas. Once gas begins to discharge from the secondary valve, adjust the secondary valve clockwise until the discharge of gas ceases. Repeat the following process until the pressure monitor displays the required pressure (1 atm). Finally, adjust valve 5 to begin the humidity test. Membrane stabilization can be performed once the above steps are completed.

Flow Testing : Once the membrane has been stabilized, adjust valve 11 and select the soap bubble flowmeter to measure flow (the size of the flowmeter can be changed depending on the size of the flow) or switch into GC for analysis (the settings of the GC can be adjusted depending on the feed).

Gas Chromatography (GC) : First, open the He gas canister until the working pressure reaches 5 kg. . Turn on the GC once gas A and gas B rise stably. Set the temperature parameters as follows: INJ=120, OVEN=150, and TCD=180. Power on the oven once the TCD rises to 100°C. Switch on the current to 100 mA once all temperatures are stable. Check all Autosample screws are fastened tightly and all injection orifices are aligned. Activate the compressor and begin testing once all parameters are checked.

Observing Membrane Formation Using a Scanning Electronic Microscope (SEM) : SEM is mainly used to observe the surface conditions of objects. It produces ultra-high-image resolution and magnification can reach thousands times or more. By contrast, conventional optical microscopes magnify samples at roughly 1,500 times. Therefore, SEM can be used to clearly observe the changes and differences in the surface morphology of membranes.

This study used SEM to observe the surface conditions of sample membranes and observe the cross-sections of the sample membranes in order to determine the thickness of the selective layer.

Membrane Hydrophilicity Measurement : This study measured the contact angle of water droplet on the surface of membrane. Hydrophilicity was determined by observing the changes in contact angle of droplet.

III. RESULTS AND DISCUSSION

The effects of PVA Concentration on Membrane GPU & WVPC

Table 1. GPU (Gas Permeation Unit) and WVPC (Water Vapor Permeate Concentration)

	GPU	WVPC % (tested 3 times)			Average WVPC (%)
Unmounted (Intake)	N/A	0.5435	0.7980	0.7784	0.7066
PVDF/PVA(1wt%)(a)	2585.363	0.7114	0.5636	0.7556	0.6769
PVDF/PVA(1wt%)(b)	29.768	0.7921	0.8229	0.7675	0.7942
PVDF/PVA(1wt%)(c)	37.453	0.6918	0.7406	0.7469	0.7264
PVDF/PVA(2wt%)(a)	9.011	1.4374	0.9969	1.1718	1.2020
PVDF/PVA(2wt%)(b)	112.066	0.8364	1.0373	0.9802	0.9513
PVDF/PVA(3wt%)(a)	1.905	3.8496	3.6573	3.5404	3.624
PVDF/PVA(3wt%)(b)	11.438	1.1691	1.7173	1.0239	1.3034
PVDF/PVA(3wt%)(c)	2.374	1.6001	1.8488	1.1208	1.5232
PVDF/PVA(4wt%)(a)	3.176	1.9343	3.0431	1.8922	2.2899
PVDF/PVA(4wt%)(b)	1.408	2.4444	3.9003	2.8116	3.0521
PVDF/PVA(5wt%)(a)	1.086	7.5101	8.0507		7.7804
PVDF/PVA(5wt%)(b)	1.566	4.4153	3.3825		3.8989
PVDF/PVA(5wt%)(c)	0.880	5.0391	5.6669	6.3856	5.6972

Table 2. Results for the average of GPU and WVPC

	Average GPU	Average WVPC (%)
Unmounted (Intake)	N/A	0.707
PVDF/PVA(1wt%)	884.195	0.734
PVDF/PVA(2wt%)	60.539	1.678
PVDF/PVA(3wt%)	5.239	2.150
PVDF/PVA(4wt%)	2.292	2.671
PVDF/PVA(5wt%)	1.177	5.784

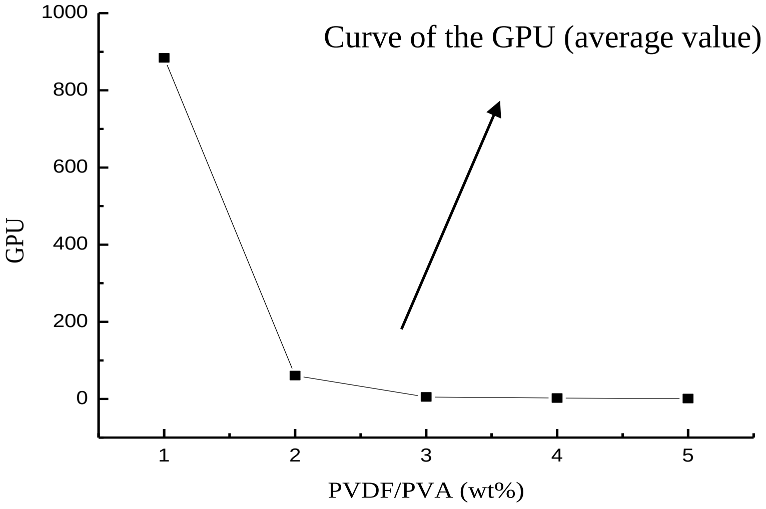


Figure 1. Effects of PVA Concentration on Membrane GPU

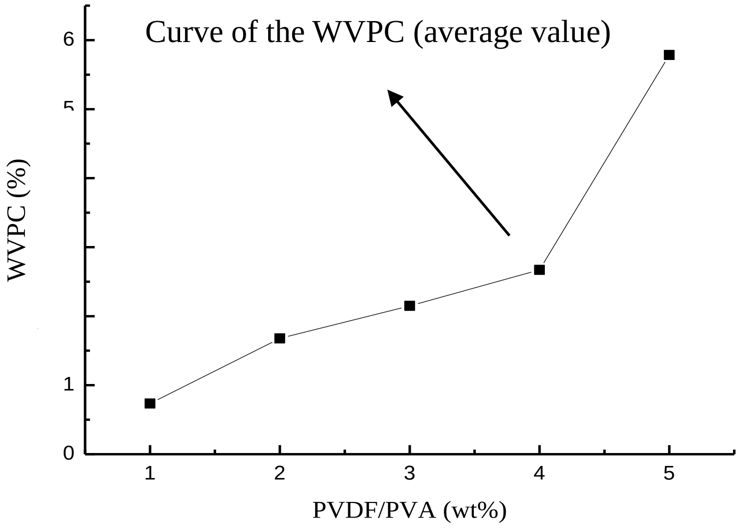
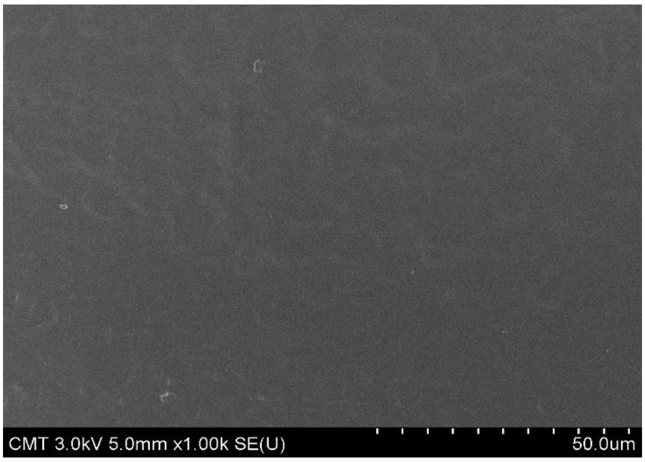


Figure 2. Effects of PVA Concentration on Membrane WVPC

Increment of high polymer concentration in the casting solution thickness increased the thickness of the surface separation layer and fabricated a more completed membrane. Increased surface separation layer thickness and membrane completeness increase permeation resistance and increased resistance reduces GPU but elevates selectivity. Figure 1 shows that GPU rapidly declined with an increase in PVA concentration, suggesting that casting solution with higher PVA concentrations fabricated thicker membranes with higher completeness. However, increased PVA concentration adversely affected productivity. Figure 2 shows that the water vapor concentration in the permeate gas increased significantly with an increase in PVA concentration. The membranes fabricated using the casting solution with a PVA concentration of 1% demonstrated a slightly higher concentrations of water vapor permeate gas than the intake gas, suggesting that the selective layer of the membrane was less complete and unable to provide favorable dehumidification properties. The membranes fabricated using the casting solution with a PVA concentration of 5% demonstrated eight times more water vapor in the permeate gas than the intake gas, suggesting that the selective layer of the membrane was complete and offered improved dehumidification. To sum up, Fig. 1 and Fig. 2 show that application of membrane separation in dehumidification possess development potential.

Structural changes in the surface and sectional formations: The results illustrated in Fig. 1 and Fig. 2 indicate that the thickness and structural completeness of the selective layer determine the dehumidification properties of the membrane. Therefore, SEM was used to observe the surface and sectional morphology of the membranes and understand the correlation between the changes in PVA concentrations and selective layer morphology. SEM images of composite membranes fabricated using casting solutions with different concentrations of PVA are illustrated in Fig. 3 to Fig. 7. SEM results show that selective layer surfaces of the membranes fabricated using the casting solution with lower PVA concentration were thinner and less complete (Fig .3). These membranes exhibited high GPUs but low water vapor concentrations in the permeate gas. Selective layer surfaces of the membranes fabricated using the casting solution with lower water potential, higher PVA concentration were thicker and more complete (Fig. 7). These membranes exhibited low GPUs but high-water vapor concentrations in the permeate gas.



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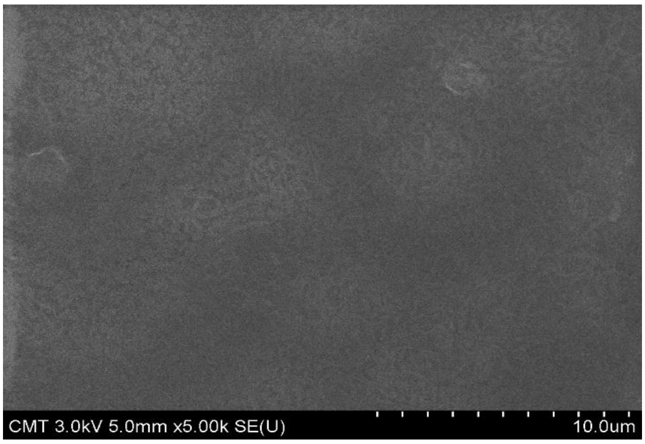

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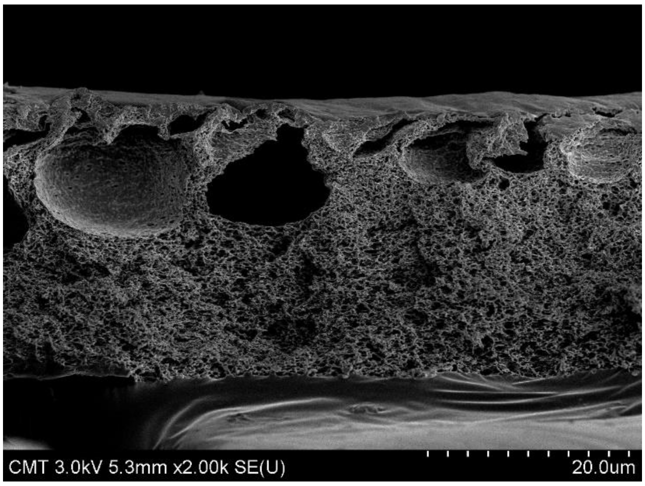
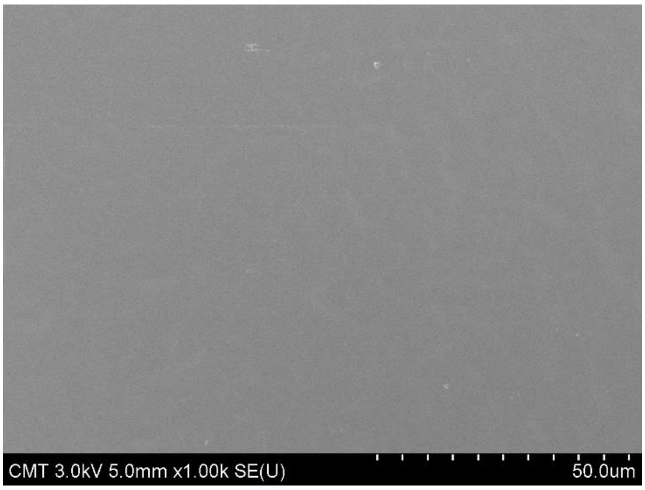


(c)

Figure 3. SEM Images of PVDF/PVA (1 wt%) Membrane: (a)(b) Membrane Surface; (c) Membrane Cross-Section



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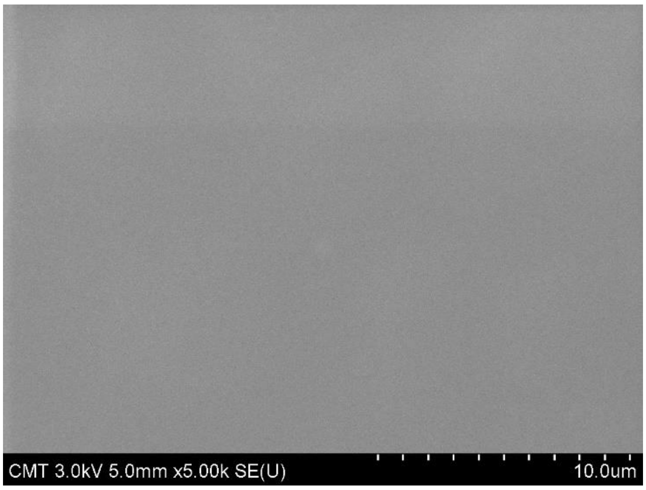

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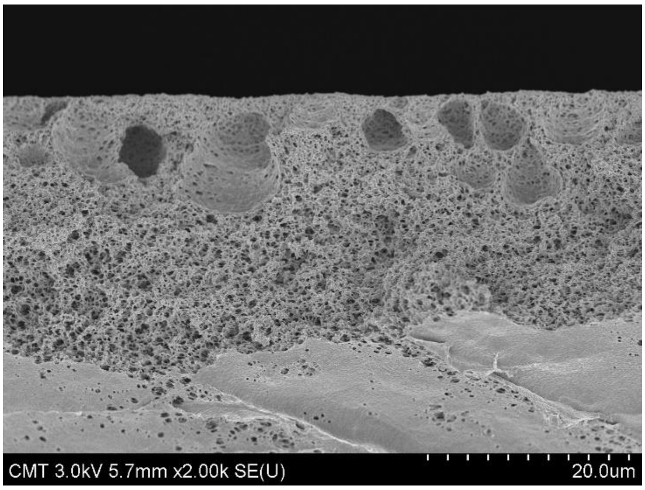

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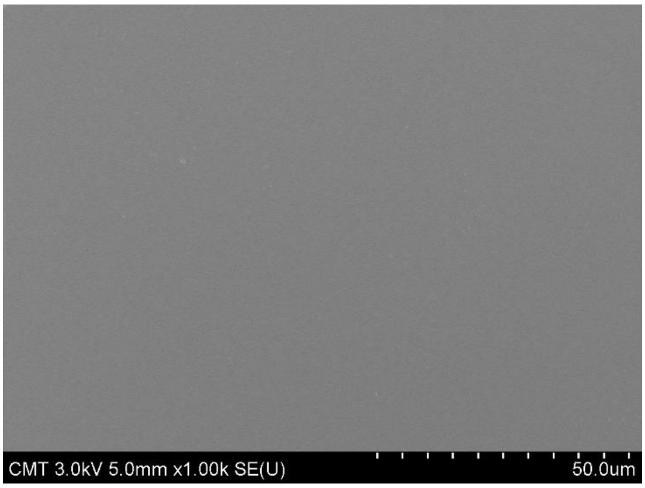
Figure 4. SEM Images of PVDF/PVA (2 wt%) Membrane: (a)(b) Membrane Surface; (c) Membrane Cross-Section



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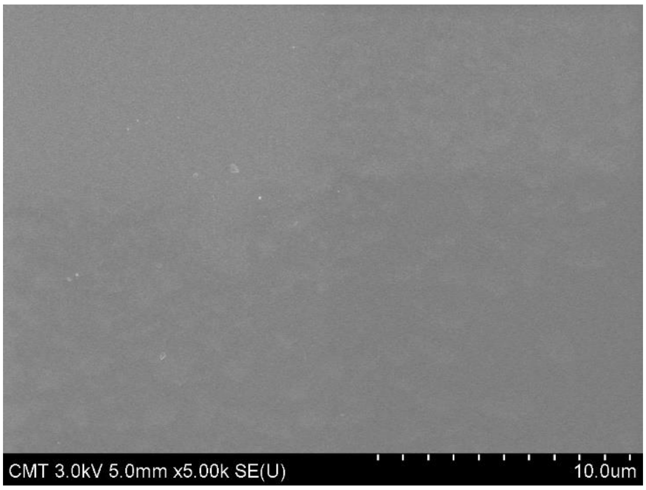

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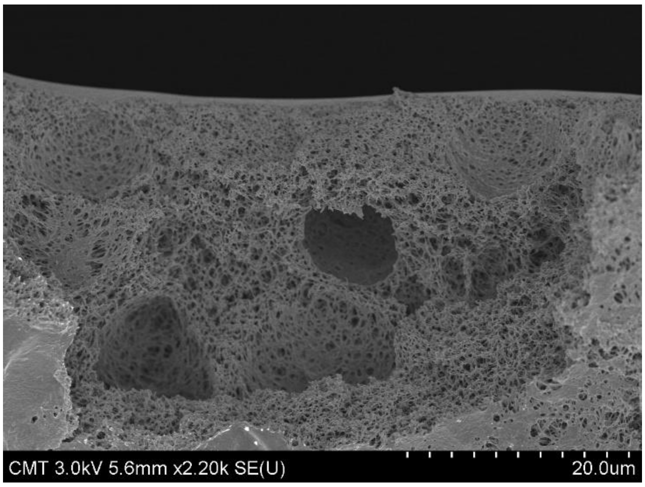

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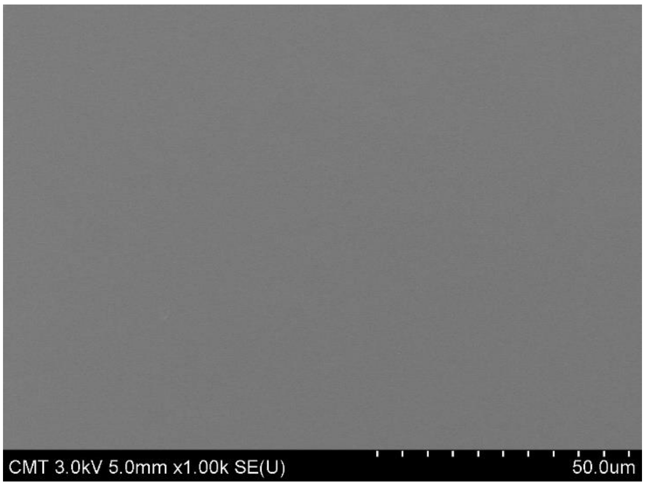
Figure 5. SEM Images of PVDF/PVA (3 wt%) Membrane: (a)(b) Membrane Surface; (c) Membrane Cross-Section



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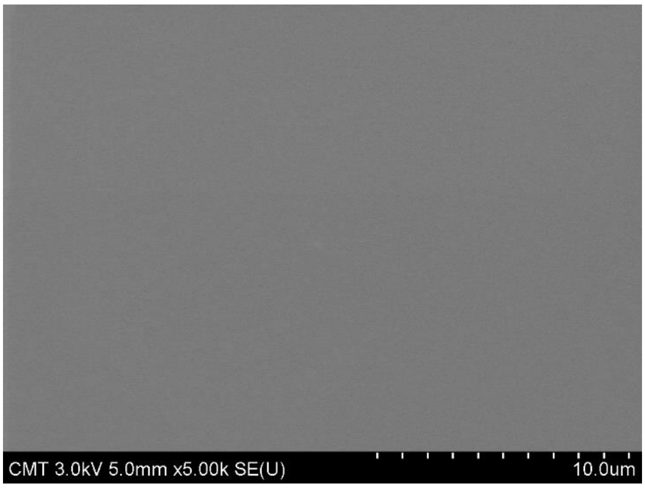

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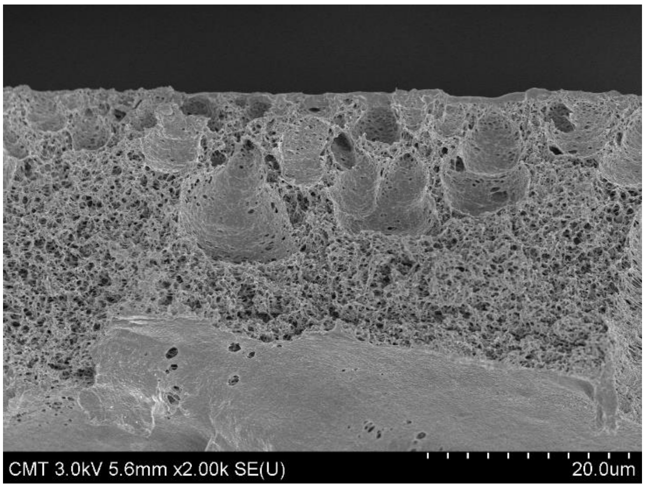

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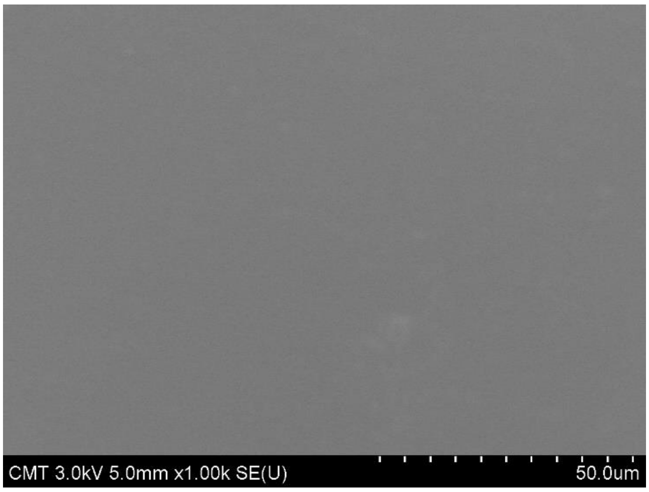
Figure 6. SEM Images of PVDF/PVA (4 wt%) Membrane: (a)(b) Membrane Surface; (c) Membrane Cross-Section



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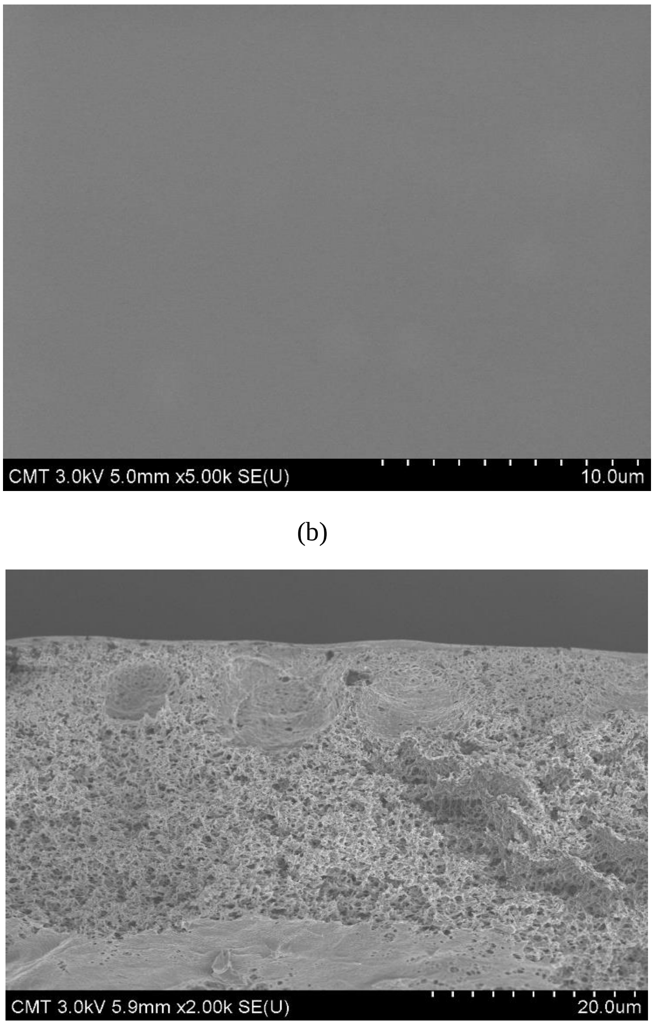

(b)

(c)

Figure 7. SEM Images of PVDF/PVA (5 wt%) Membrane: (a)(b) Membrane Surface; (c) Membrane Cross-Section

Membrane hydrophilicity : Liquid droplets are administered onto solid surfaces. Once a gas-liquid-solid equilibrium is achieved, the angle of the liquid-solid contact interface (θ) becomes the contact angle (°) between the fluid and the solid. When water is used as the test liquid, a smaller contact angle denotes a higher hydrophilicity. By contrast, a larger contact angle denotes a smaller hydrophilicity.

Table 3. Membrane-Water Contact Angle Test Results

	PVA (1 wt%)	PVA (2 wt%)	PVA (3 wt%)	PVA (4 wt%)	PVA (5 wt%)
Contact Angle (1)	45.5°	63.3°	68.0°	48.9°	89.2°
Contact Angle (2)	48.6°	72.0°	59.7°	34.8°	92.2°
Contact Angle (3)	44.1°	69.2°	72.0°	33.7°	92.2°
Contact Angle (4)	46.7∘	58.1∘	58.7∘	53.8∘	98.0∘
Contact Angle (5)	43.0∘	65.4∘	54.5∘	50.0∘	92.3∘

Contact Angle (6)	52.5°	50.8°	43.5°	67.6°	85.8°
Contact Angle (7)	42.1°	70.0°	64.9°	66.3°	103.1°
Contact Angle (8)	50.9°	62.3°	63.1°	70.0°	80.5°
Contact Angle (9)	53.7°	67.0°	60.9°	70.8°	81.4°
Contact Angle (10)	45.6°	65.6°	59.2°	58.5°	77.0°
Contact Angle (Ave.)	47.3°	64.2°	60.5°	55.4°	89.2°

Figure 8 indicates that for the PVA (2 wt%), PVA (3 wt%), and PVA (4 wt%) membranes, the contact angles decreased as PVA concentration increased, implying an increase in hydrophilicity. Among the membranes, the contact angles of the PVA (1 wt%) and PVA (5 wt%) showed differing trends. This may be due to the influence of different in surface coarseness.

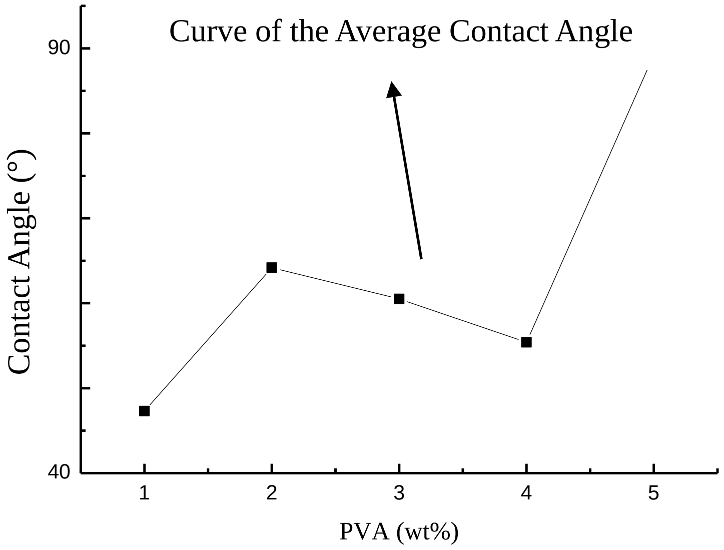

Figure 8. Effects of PVA Concentrations on the Hydrophilicity of the Composite Membranes

IV. CONCLUSION

This study used PVDF as base films and fabricate selective layers using five different concentrations: PVA (1wt%), PVA (2wt%), PVA (3wt%), PVA (4wt%) and PVA (5wt%). Analysis on gas influx, SEM and membrane hydrophilicity has been performed.

Permeation results indicated that the selective layers fabricated with PVA (1 wt%) and PVA (5 wt%) achieved the highest and lowest GPUs respectively. Results from GC analysis show that selective layers fabricated with PVA (5 wt%) and PVA (1 wt%) achieved the most and least favorable dehumidification performance, suggesting that dehumidification performance improved with increase in highly hydrophilic polymer concentrations. Based on preliminary findings, this study confirmed that PVA Composite membrane separation can be used for dehumidification and believes that high-performance dehumidification membranes can be developed with continuous improvement membrane characteristics can be made, and it is potential to “displace” the conventional condensation- dehumidification by reduce energy consumption on the air-conditioning.

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