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Air Dehumidification using Ionic Liquid-Based Fiber Bundle Membrane Contactor

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ABSTRACT

Air dehumidification is essential since excess moisture in the buildings causes discomfort to the occupants, encourages the production of air pathogens such as mold or mildew, and causes corrosion and rotting that degrade building materials. Existing moisture removal processes are mainly focused on condensation and desiccant (liquid or solid) techniques with direct contact between air and desiccant. However, these methods are energy-intensive, or desiccant might be lost or cause corrosion in the process. The main objective of this study is to investigate an ionic liquid-based liquid desiccant absorber based on a membrane fiber bundle. A novel membrane contactor system was fabricated with a bundle of 10,000 polypropylene fibers. Each fiber has 0.3 micron outer diameter, with ionic liquid flowing inside, and air flowing outside. The fibers provide a high contact area among phases: 1.4 m^2 contact surface area in a 0.00015 m^3 volume (9,333 m^2/m^3 ratio of surface area to volume). The ionic liquid as a sorbent has selectivity for water vapor (i.e., the ionic liquid has higher affinity for water vapor) prevents the loss of solvent in the operation due to negligible volatility, provides fast diffusion due to low viscosity compared to common ionic liquids, and has high affinity and solubility in water. The dehumidification capacity of the prototype membrane system was experimentally investigated using six modules with 10,000 fibers each. The experimental results show that the ionic-liquid based membrane system can effectively remove excess moisture from the air. The novel fiber bundle dehumidification system has a total system volume of 0.00798 m^3 (7.98 L) and active heat and mass transfer surface area of 8.4 m^2. It achieved an average dehumidification of 320 ± 25 W with a volumetric air flowrate of 3.1 m^3/min (108 ft^3/min).

1. INTRODUCTION

The humidity is one of the essential control parameters for indoor environment quality as the excess humidity in the buildings can discomfort the occupants, induce the production of air pathogens such as mold, mildew, or viruses, and cause corrosion and rotting which might result in degradation of the building materials (Qu et al., 2018). Furthermore, the excessive humidity in the buildings increases the heat load on the HVAC system (Yang et al., 2015). Currently, the residential building systems are responsible for 18% of the overall US energy consumption, where space cooling is responsible for 7% of this entire energy usage (International Energy Agency, 2019). Undoubtedly, efficient and low-cost air dehumidification is of great importance for energy savings.

The current air dehumidification processes are mainly focused on condensation (i.e., dew point method) and desiccant (liquid or solid) dehumidification processes. When the moisture of air is removed via condensation method by reducing the air temperature below its dew point temperature (Liu et al., 2019), this method causes excessive energy usage due to overcooling the air stream for excessive moisture removal and reheating the air stream to occupants' comfort. In the desiccant processes, sorption technology (adsorption or absorption) is utilized to capture excessive water in the air. Even though desiccant processes eliminate the overcooling and reheating in the conventional air conditioning systems, the regeneration of the solid desiccant systems requires high temperature and the potential carryover of the liquid in the liquid desiccant system might cause corrosion in the HVAC ductwork and other components. In recent years, membrane-based separation techniques have gained attention for air dehumidification due to their structural flexibility, continuous operation, and high dehumidification efficiencies (Yang et al., 2015). Membrane-based dehumidification systems use the chemical potential gradient (concentration or pressure gradient) between feed and permeate sides of the membrane as a driving force to remove water vapor from the air (Bansal et al., 2011). Membrane contactor technology combines the membrane separation and absorption technologies while offering a high surface area by enhancing the contact area between the gas and liquid phase. A membrane provides the interface and where a liquid sorbent stipulates the selectivity for water vapor. The liquid phase in the membrane contactor can be organic liquid, which can be disadvantageous due to its high volatility. However, ionic liquids (ILs), low melting point salts composed entirely of ions (MacFarlane et al., 2017), could be an alternative absorbent in the membrane contactors when an ionic liquid used in the membrane possesses negligibly low vapor pressure to prevent the solvent loss, low viscosity for fast diffusion, and high solubility of water in the given IL for the high amount of absorption (Kudasheva et al., 2016). Besides, the IL should be ideally non-halogenated (i.e., fluoride-free) to prevent the formation of hazardous substances (i.e., hydrofluoric acid).

Previous research showed that supported ionic liquid membranes (i.e., ionic liquid-loaded flat membrane sheets) showed promising gas and air dehumidification results (Kudasheva et al., 2016; Scovazzo, 2010). In this study, we designed a novel ionic liquid-based fiber bundle membrane contactor unit for continuous air dehumidification for buildings. This novel membrane system based on tubular fiber bundles with the enhanced surface area for water sorption experimentally demonstrated 320 ± 25 W dehumidification capacity at an air inlet condition of 24.4 ± 0.2°C (75.9 ± 0.2°F) and 50.5 ± 0.5 %RH. This new tubular fiber bundle geometry demonstrated an improved dehumidification capacity per volume (40 kW/m^3) compared to our previous planar geometry designed ionic liquid-membrane system (22 kW/m^3).

2. EXPERIMENTAL APPARATUS

The air dehumidification experiment was performed using an in-house designed unit, as shown in Figure 1. The unit consists of the absorber, desorber, strong solution tank, weak solution tank, a solution-oil heat exchanger (SOHX), a solution-water heat exchanger (SWHX), silicon oil bath, and water bath. As shown in Figure 2, the absorber was constructed using six tubular membrane contactors in a parallel configuration. Each membrane contactor (3M, Liqui-Cel Membrane Contactor) contains 10,000 hydrophobic 0.3 micron diameter polypropylene fiber bundles in a polyethylene shell. The volume of shell side and lumen side of each membrane contactor is 0.0004 m^3 and 0.00015 m^3, respectively. The total volume of the membrane contactor with flange connections is 0.00133 m^3. The surface area of a membrane contactor is 1.4 m^2. The total available surface area in the membrane unit is 8.4 m^2. The shells of each membrane contactor were carefully cut for airflow into the membranes (Figure 2). The unit is housed in an environmental chamber to maintain the humidity and the temperature of the air in the experiment at the desired set point. The liquid phase used in this study is a 1-ethyl-3-methylimidazolium methanesulfonate with a small additive of benzotriazole as a corrosion inhibitor (Sorbionic04, Proionic, Inc). The concentration of water in strong and weak solutions were measured using the Refractive Index instrument (Milton Roy Company, Abbe 3L) and calculated with a calibration curve established at a known concentration of water in the mixtures. The solution and air temperatures were measured using platinum Resistance Temperature Detectors (RTDs) with an accuracy of ± 0.03°C. The solution flow rates of water, silicon oil, and strong solutions were measured using a Coriolis meter with an accuracy of ± 0.5 % and controlled by flow control needle valves. The relative humidity of the air in the chamber was measured using Vaisala HMT 337 humidity sensor with an accuracy of ± 1.7 %RH. The flow rate of the air stream was measured using Veltron II differential pressure transducer with a Pitot Traverse Station (Air Monitor Corporation) with an accuracy of ± 4%, and the fan was controlled using 0-24 VDC power supply.

In the air dehumidification experiment, as shown in Figure 3, the weak solution is preheated in the solution-oil heat exchanger (SOHX) before entering the desorber. In the desorber, the weak solution was heated to 150°C (302°F) to evaporate the water, leaving the desorber as a strong solution. Then, the strong solution was cooled down to 23-24°C (73-75°F) at the solution-water heat exchanger (SWHX). After the temperature of the strong solution was lowered, the strong solution flows in the membrane module, and the air simultaneously flows through the membrane modules in the counter-flow arrangement where the water in the air is absorbed by the IL. The solution leaves the absorber as a weak solution and continues in the cycle.

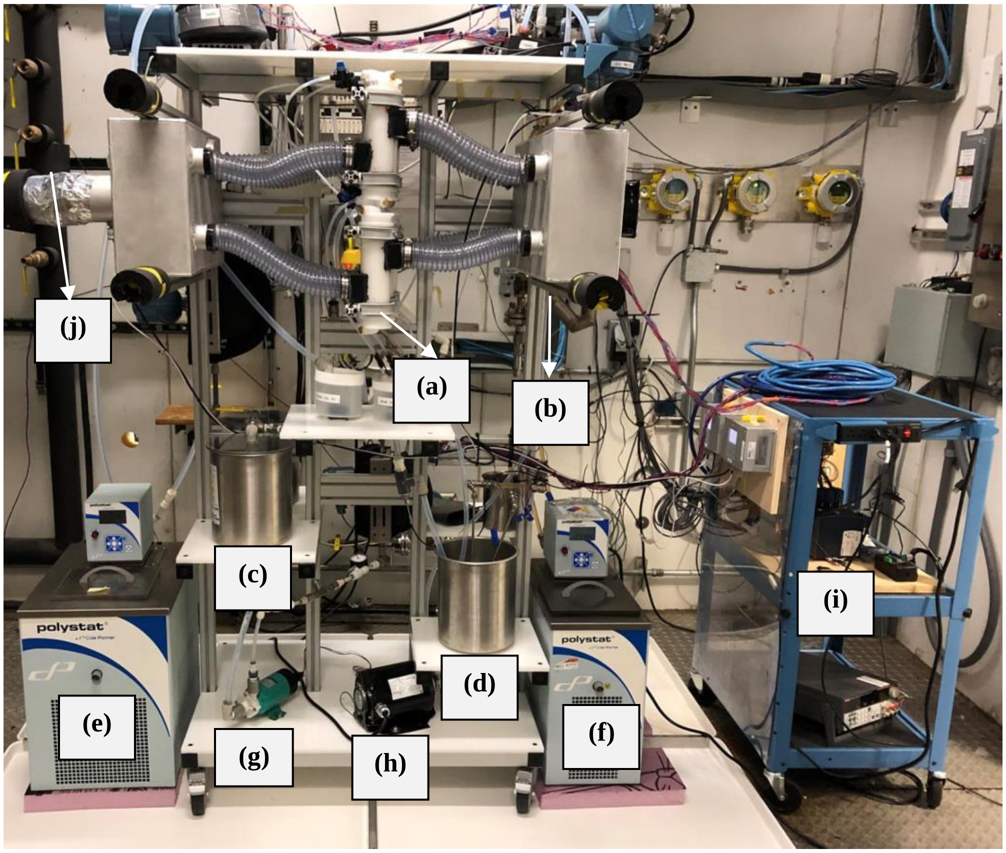

Figure 1: Experimental set-up for a novel air dehumidification module where (a) membrane fiber bundle module, (b) inlet air header, (c) strong solution tank, (d) weak solution tank, (e) cooling water bath, (f) heating oil bath, (g) weak solution pump, (h) strong solution pump, and (i) data acquisition and control unit, and (j) air flow measurement station

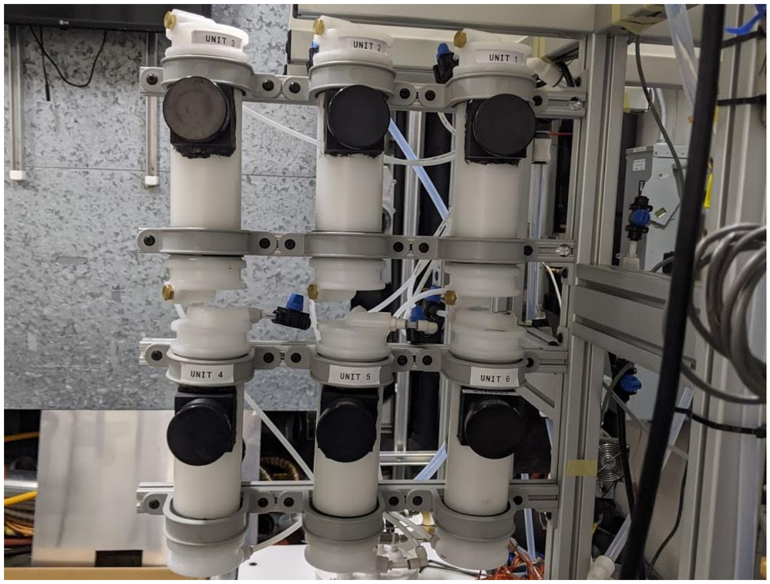

Figure 2: Six membrane contactors in a parallel configuration. The black holes are the air inlets, shown capped.

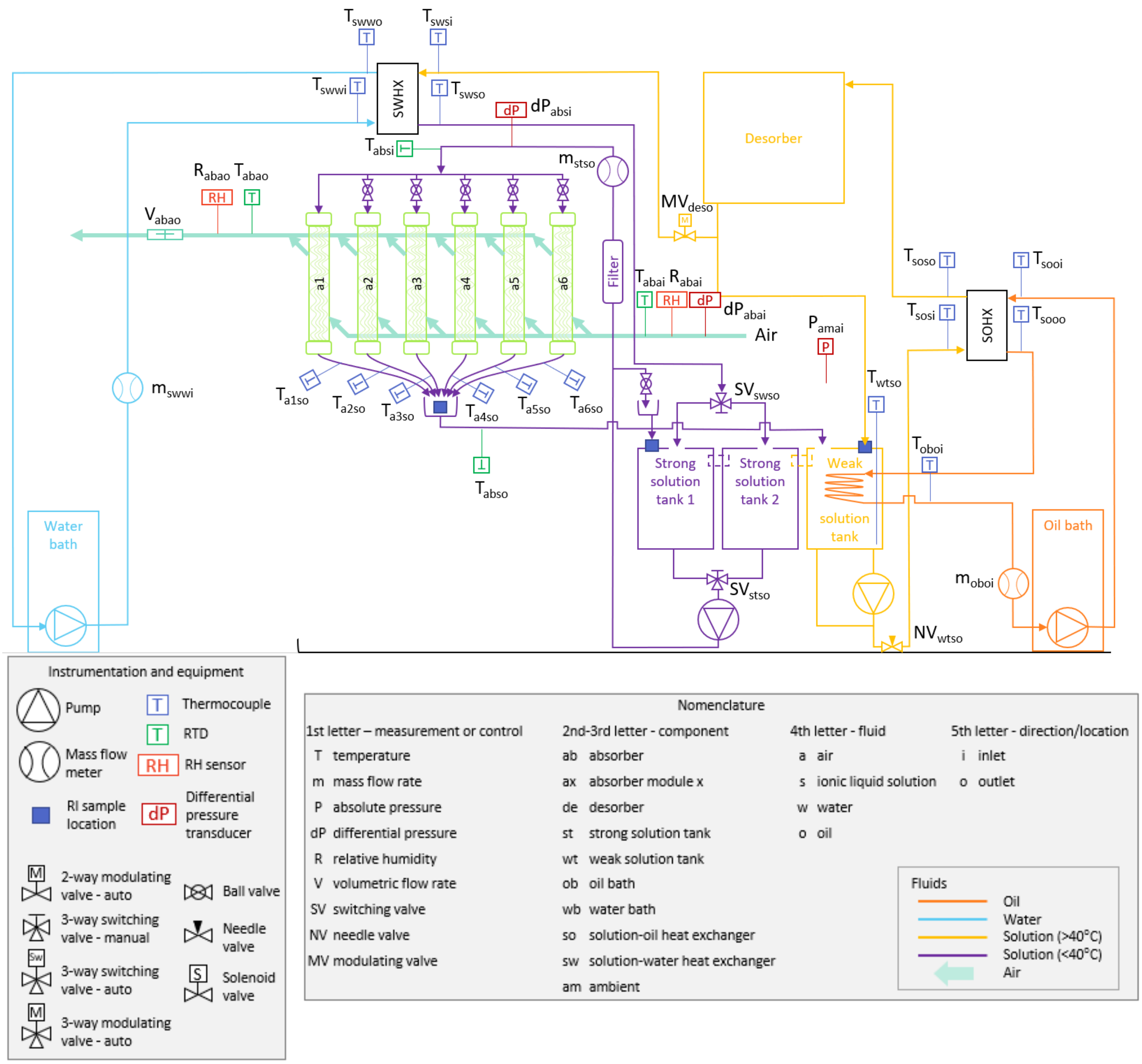

Figure 3: Process and instrumentation diagram of the air dehumidification unit. Naming convention:1st letter represents the measured property or control unit, 2nd and 3rd letter represent the system component, 3rd letter represent the type of fluid, and 4th letter represent the direction of the flow.

3. RESULTS AND DISCUSSION

Air dehumidification using tubular fiber bundles was performed in an environmentally controlled chamber at 24.4 ± 0.2°C. The air entered the unit with a flow rate of 3.1 m^3/min (108.1 ft^3/min) at 24.4 ± 0.2°C (75.9 ± 0.2°F) and 50.5 ± 0.5 %RH. Figure 4 shows the RH and T of the inlet and outlet air stream during the steady-state operation. The total solution inlet flow rate was 0.0067 kg/s (0.0147 lb/s) with a solution-water mass fraction of 0.873. The membrane system reduced the air humidity to 37% RH, highlighting the dehumidification capacity of the membrane bundle tubes. The temperature of the air was increased from 24.4°C to 25.5°C, which is attributed to the heat of water dissolution in the solution being transferred to the outlet air. The air side pressure drop in the parallel configuration was 758 Pa (0.11 psi or 3 inch of H_2O) at an inlet air flow rate of 3.1 m^3/min (108.1 ft^3/min). The low air side pressure drop in the tube bundle membrane was achieved by altering and modifying the air side inlet and outlet ports on the shell from 0.00635 m (0.25 inch) to 0.0508 (2 inch) diameters. The solution side pressure drop in parallel configuration (as illustrated in Figure 3) was 16547.4 Pa (2.4 psi) at a solution flow rate of 0.0067 kg/s (0.0147 lb/s). The high pressure drop across the solution side was due to the small diameter (0.3 µm) tubes.

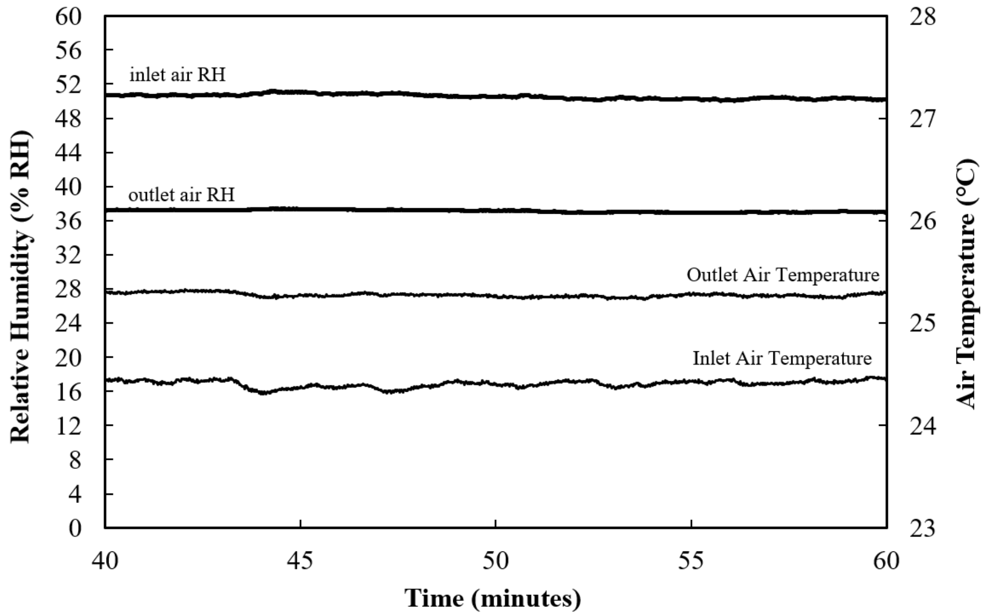

Figure 4: Steady-state experimental measurements of ambient air inlet and outlet conditions

As shown in Figure 5, the system reduced air humidity ratio from 0.0098 kg_w/kg_{da} to 0.0076 kg_w/kg_{da} with 0.0056 kg/s flow of air. This is a rate of 0.00013 kg water vapor per second removed from the air, and in the process the solution mass fraction (mass of solution/ (mass of water + mass of solution)) reduced from ~0.88 to 0.85. The system achieved a total dehumidification capacity of 320 Watts.

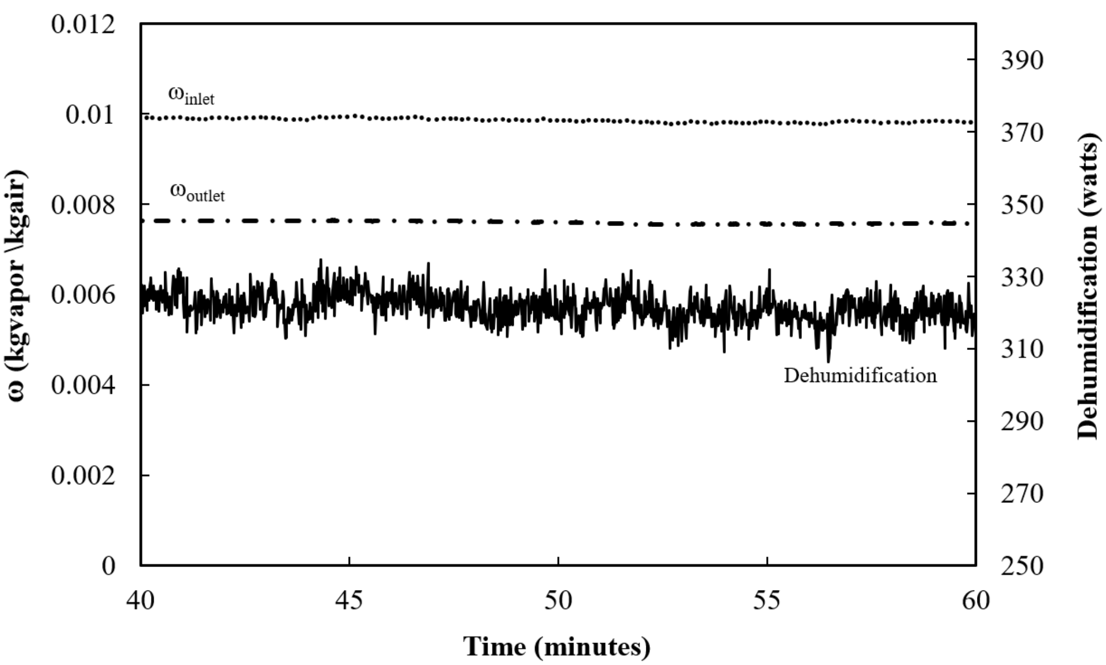

Figure 5: Steady-state experimental measurement of dehumidification capacity and air specific humidity (ω)

Figure 6 shows the performance of each of the six membrane contactors during the dehumidification process. The 320 W heat of dehumidification increased the average outlet temperature of the solution from 22.4°C to 29.8°C at the outlet air stream. As shown in Figure 6, the majority of the dehumidification was achieved in modules 3, 4, 5, 6 as the solution outlet temperatures in these modules were above the average outlet solution temperature. The discrepancies in module 4 at around 43 minutes and 58 minutes are attributed to air bubbles at the solution inlet. The air bubbles were forced out before the solution was able to re-wet the membrane tubes. The underperformance of modules 1 and 2 is ascribed to the relatively elevated pressure drop due to an inefficient wetting of the membranes fiber bundles resulting in lower solution flow rates.

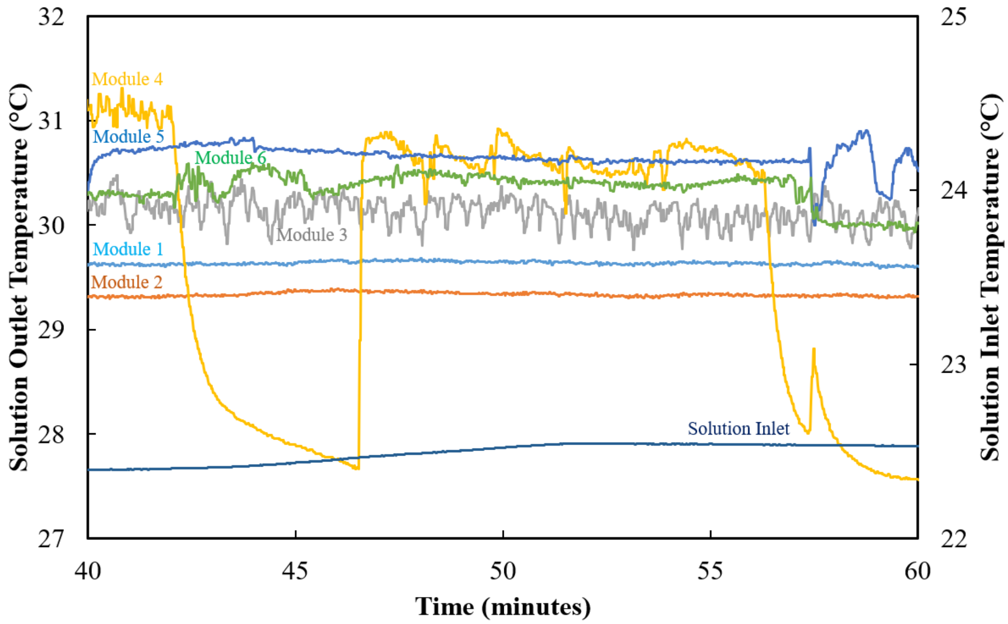

Figure 6: Steady-state experimental measurements of absorber inlet and outlet solution temperature for the six modules running in parallel. One module (module 4) appeared to have intermittent solution flow

As shown in Table 1, the current novel membrane system possesses a higher active surface area compared to the previous flat sheet membrane systems resulting (D Chugh et al., 2017, D Chugh et al., 2019a**,** Kumar et al., 2020) in approximately twice the performance of the flat-sheet membrane absorber system (Kumar et al., 2020).

Table 1: The comparison of the absorber systems

	Generation 1 (D Chugh et al., 2017)	**Generation 2** (D Chugh et al., 2019a)	**Generation 3** (Kumar et al., 2020)	**This study**
Number of panels or modules	4	7	13	6
Active surface area (m^2)	0.42	0.92	1.89	8.4
Active plate or module volume (m^3)	0.0084	0.0080	0.012	0.00798
Active surface area/volume ratio (m^2/m^3)	50	115	159	9333

4. CONCLUSION

The current novel membrane system based on tubular fiber bundles experimentally demonstrated 320 ± 25 W dehumidification capacity at an air inlet condition of 24.4 ± 0.2°C and 50.5 ± 0.5 %RH.

The following conclusions were drawn from the experiments:

- The novel fiber bundle dehumidification system had a total volume of 0.00798 m^3 (7.98 L) and active heat and mass transfer surface area of 8.4 m^2. The new system achieved an average dehumidification density of 40 kW/m^3, which is approximately twice the performance of the flat-sheet membrane absorber system (Kumar et al., 2020).
- Compared with the previous planar absorber (D Chugh et al., 2019b), this membrane fiber bundle system achieved 23% more dehumidification using 32% less volume.
- The 80% compactness improvement is particularly impressive considering that the previous planar system was isothermal (internally cooled), while the fiber bundle prototype in this work was adiabatic. The improvement is ascribed to the favorable surface area-to-volume ratio of the current prototype (9.333 m^2/m^3 compared to 159 m^2/m^3), arising from the very small diameter (0.3 mm) fibers.
- The airside pressure drop in the parallel configuration was 758 Pa (0.11 psi, or 3 inch water column) at a volumetric airflow rate of 3.1 m^3/min (108.1 ft^3/min).
- The solution side pressure drop in the parallel configuration was 2.4 psi at a solution mass flow rate of 0.0067 kg/s (0.0147 lb/s).

The results showed that membrane fiber bundles are a promising technology for air dehumidification. The system design and geometry showed 80% improvement compared to the previous planar geometry designed membranes (40 kW/m^3 vs. 22 kW/m^3). The technology is currently under further development for custom design fiber bundles, geometry optimization, and embedding an internal cooling to make the system isothermal rather than adiabatic.

NOMENCLATURE

Main Text:

HVAC	Heating, Ventilation and Air Conditioning
P	Absolute Pressure
RH	Relative Humidity
RTF	Resistance Temperature Detector
SOHX	Solution-Oil Heat Exchanger
SWHX	Solution-Water Heat Exchanger
T	Temperature

P&ID (Figure 3):

1st letter

dP	Differential Pressure
m	Mass flow rate
MV	Modulating Valve
NV	Needle Valve
R	Relative Humidity
SV	Switching Valve
V	Volumetric Flow Rate

2nd and 3rd Letter

ab	absorber
am	ambient
ax	absorber module
de	desorber
ob	oil bath
so	solution-oil heat exchanger

st	strong solution tank
sw	solution-water heat exchanger
wt	weak solution tank
wb	water bath

4th Letter

a	air
o	oil
s	ionic liquid solution
w	water

5th Letter

i	inlet
o	outlet

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