Paper ID APEN-MIT-2020_313
Applied Energy Symposium: MIT A+B
August 12-14, 2020 • Cambridge, USA

# Performance Analysis of a Membrane-based Ionic Liquid Desiccant (ILD) Dehumidifier

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Abstract—Air dehumidification through cooling is an energy-intensive process, which consumes about 20-40% of the overall energy for air-conditioning. Liquid desiccant dehumidification can separate dehumidification from space cooling and has potential to improve the cooling efficiency and reduce the overall energy consumption for air-conditioning. However, the drawbacks such as liquid carryover and corrosion, membrane contamination and blocking, limit its application. To eliminate these problems, a new dehumidifier using nonporous membrane and ionic liquid desiccant (ILD) was developed. The dehumidification performance of the new dehumidifier was characterized through a series of lab tests. Test results indicate that the new dehumidifier can achieve a moisture removal rate up to 180.3 g/h and a dehumidification effectiveness up to 12.7%. A parametric study found that the dehumidification performance is sensitive to the flowrates of the air and the ILD solution. A higher mass flow ratio between the ILD solution and the air could result in better dehumidification performance.

*Keywords—ionic liquid desiccant, dehumidifier, nonporous membrane, moisture removal rate, experimental study*

## I. INTRODUCTION

Buildings are the primary users of electricity in US—75% percent of all US electricity is consumed within buildings [1]. The largest electricity consumer in buildings is for space conditioning. In the hot and humid area, space conditioning alone consumes 30% of total electricity uses [2]. Air dehumidification contributes 20-40% to the overall energy consumption for air-conditioning [3]. The conventional air dehumidification is to condense water vapor in the air at a temperature lower than the air dew point temperature. The cooled air often needs to be reheated. Therefore, significant amount of energy is consumed in the overcooling and reheating processes. Liquid desiccant dehumidification, in which the moisture is absorbed from the air by the concentrated liquid desiccant solution at room temperature, is a promising alternative method for air dehumidification [2]. A higher chiller COP (Coefficient of Performance) and significant energy saving can be achieved by using liquid desiccant for air dehumidification. The diluted liquid desiccant can be regenerated using low-grade heat sources such as solar thermal energy or waste heat of industrial process, which further contributes to energy conservation [4]. However, two main drawbacks of conventional liquid desiccant dehumidification systems, liquid carryover and corrosion, limit its application. The liquid carryover usually occurs when flowing from the packed-type liquid desiccant dehumidifier, and the commonly used liquid desiccant such as lithium chloride is easy to corrode metals [5].

To solve the abovementioned problems, membrane-based liquid desiccant dehumidifier was developed [6] and ionic liquid has been used as the liquid desiccant [7,8]. Membrane-based liquid desiccant dehumidifier uses semipermeable membranes to separate the water vapor from the processing air and absorb the water vapor using the liquid desiccant. Ionic liquids refer to the salts comprised of organic cations and inorganic or organic anions. Some Ionic Liquids have negligible or no vapor pressure and high solubility in water, low or no corrosion to metals [9]. The commonly used membrane is porous membrane with the pore size at about 0.1 μm [6]. However, the performance of the porous membrane could degrade over time if the pores of the membrane are blocked by the contamination. Nonporous membranes don't have this problem. However, the study on the dehumidification using nonporous membrane is very rare [10], especially when combined with ionic liquid.

A new dehumidifier using nonporous membrane and ionic liquid desiccant (ILD) has been developed. The dehumidification performance of a benchtop prototype of the new dehumidifier was tested under various operating conditions. The impacts of air flowrate and ILD solution flowrate on the dehumidification performance were investigated through a series of lab tests. The experimental apparatus and the test results are presented in this paper.

## II. EXPERIMENTAL APPARATUS OF A MEMBRANE-BASED IONIC LIQUID DESICCANT (ILD) DEHUMIDIFIER

The developed benchtop prototype dehumidifier is shown in Fig. 1. The prototype utilizes multiple tubular membranes with mesh reinforcement to minimize uneven distribution of the liquid desiccant and membrane deflection as well as leakage issues. This design also improves strength of the dehumidifier compared with previous designs using flat sheet membranes [8]. A variance of the Nafion® perfluorinated sulfonic acid (PFSA) nonporous membrane was used to make the membrane tubes ($\Phi$ 4.5mm). The scanning electron microscope (SEM) images of this nonporous membrane and a common porous membrane are shown in the left of Fig.1. Different from the porous membrane, the surface of the nonporous membrane is smooth and there are few pathways for the moisture to pass through. The aqueous solution (70% by weight) of an ionic liquid—1-Ethyl-3-methylimidazolium acetate ([EMIM][OAc])—was used as the ILD. The thermophysical properties of the ILD using [EMIM][OAc] was reviewed and compiled by Qu et al. [9]. The prototype has a cross-counter flow pattern between the ILD solution and air—ILD flows from bottom to top through the membrane tubes to ensure all the tubes are fulfilled with the solution, and the air flows in from one side of the prototype at the top and flows from the bottom on the opposite side, as shown in right side of Fig. 1. The dimensions of the prototype is 0.15m x 0.1m x 0.35m.

An experimental apparatus to test the performance of the prototype dehumidifier has been built in a climate chamber at ORNL. The apparatus is comprised of three parts: the benchtop prototype dehumidifier, an air loop, and an ILD solution loop. The schematic and the photos of this apparatus are shown in Fig. 2.

In the air loop, a fan with an inverter, a damper, two combined humidity and temperature sensors, and an air flowmeter were installed. The air entering the dehumidifier is from the climate chamber, which is maintained at the desired temperature and humidity. The dehumidified air is discharged to the climate chamber. The flow rate of air can be adjusted using the inverter.

In the ILD solution loop, two pumps, two combined liquid density and flow meters, two solution tanks (with a stainless-steel heat exchanger inside), and a refrigerated circulating water bath were installed. The ILD solution with required concentration and temperature is stored in one solution tank and pumped through the dehumidifier. The diluted ILD solution flows to the other solution tank. Temperature of the ILD solution in the storage tank is maintained with the water bath through the heat exchanger inside the tank. The refrigerated circulating water bath can warm or cool the ILD solution to a desired temperature between 20 °C and 35 °C. The flow rate of the ILD solution can be adjusted using a needle valve in the solution loop.

The flow rate, temperature, and humidity of the air, as well as the concentration, temperature and flow rate of the ILD solution at the inlet and outlet of the dehumidifier are measured every second and all the measured data are saved in a computer at a user specified time interval (e.g., every minute). Table 1 lists the specifications of the measurement instrumentation.

Moisture removal rate (MRR) and dehumidification effectiveness (ε) are used to evaluate the dehumidification performance of the dehumidifier. MRR represents the weight of water vapor removed from the air per hour (g/h);

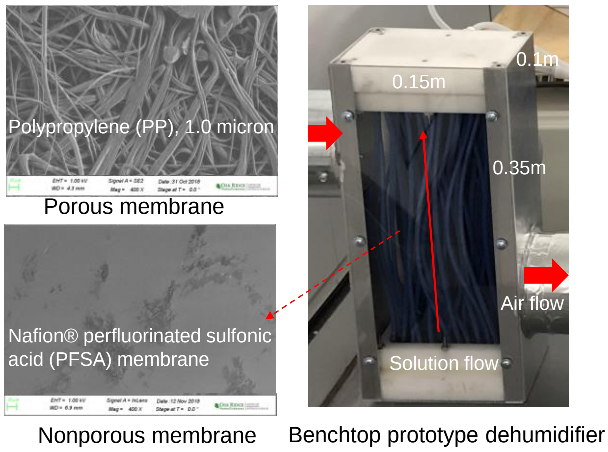


Fig. 1 Benchtop prototype of a membrane-based dehumidifier.

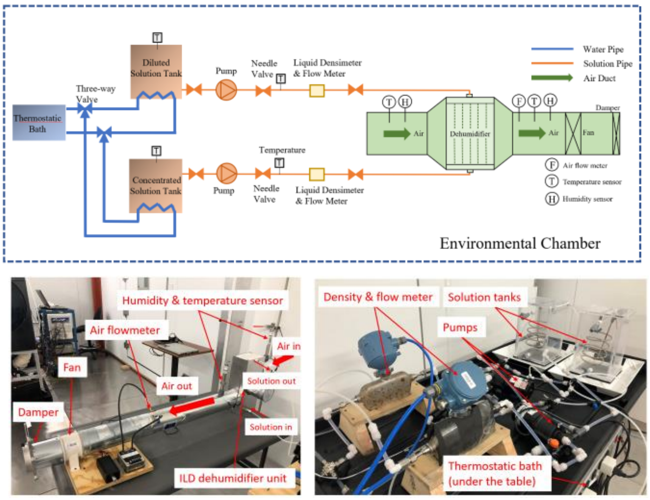


Fig.2 Experimental apparatus for testing the prototype dehumidifier.

TABLE 1. MEASUREMENT INSTRUMENTATION.

| **Measured value** | **Instrument** | **Range** | **Uncertainty** |
|---|---|---|---|
| Temperature of ILD | RTD [Omega PR-20 series, Class “A” DIN] | −50 – 260°C (instrument range) | ±0.15°C |
| Temperature of ILD in the tanks | T-type thermocouple probes [Omega] | −270–370°C | ±0.5°C |
| Flow rate of ILD | MicoMotion ELITE CMFS010H Coriolis | 0–110 L/h | ±0.05% of rate |
| Density of ILD | MicroMotion ELITE CMFS010H Coriolis | 0–4000 kg/m$^3$ | ±0.2 kg/m3 |
| Flow rate of air | Setra’s Model 264 Differential Pressure Transducer | -0.05-0.05”W.C. | ±0.25%FS |
| Humidity and temperature of air | HMT330 Humidity and Temperature Transmitters | 0-100% RH, −40–180°C | ±(1.5 + 0.015 x reading) %RH, ±0.2°C |

dehumidification effectiveness is the ratio between the actual and maximum possible water vapor absorption rate in dehumidifier, as shown in Eqs. (1) and (2).

$$MRR = AirFlow * \rho_{air} * (w_{air,in} - w_{air,out}) \quad (1)$$

$$\varepsilon = (w_{air,in} - w_{air,out})/(w_{air,in} - w_{sol,in}) \quad (2)$$

Where AirFlow is the flow rate of air ($m^3/h$), $\rho_a$ is the density of air ($kg/m^3$), $w_{air,in}$ and $w_{air,out}$ are the humidity ratio of inlet and out air (g/kg), respectively, $w_{sol,in}$ is the equivalent humidity ratio of inlet ILD solution (g/kg).

## III. Experimental Results of Dehumidification Performance

A series of tests were conducted to evaluate the performance of the dehumidifier. The conditions of one of the tests are shown in Table 2 and the measured data during the test are shown in Fig. 3. The inlet air condition in this case, 32.2°C dry bulb temperature and 63% relative humidity (RH), is a typical outdoor air condition. Measured data showed that the RH was reduced to 59.2% when the air flowed out of the dehumidifier while the air temperature remained nearly constant. On the other hand, the ILD solution temperature was warmed from 20.5 to 31°C after passing through the dehumidifier. The temperature rise was due to the heat transfer between the air and the solution. The larger temperature change in the ILD solution than that in the air is a result of a high mass flow ratio between the air and the ILD solution (12:1). In this case, the air flow at the inlet is 24.5 g/s while the flow rate of the ILD solution at the inlet is 2.04 g/s. The measured MRR of this test was 124.4 g/h and ε was 9.4%.

A parametric study was conducted to assess the sensitivity of the dehumidification performance in response to changes in operating conditions. The studied parameters included air flowrate and ILD solution flowrate.

TABLE 2. CONDITIONS OF ONE OF THE TESTS.

| Variable | Symbol | Unit | Measured data |
|---|---|---|---|
| Temperature of inlet ILD | RTD_3 | °C | 20.5 |
| Temperature of outlet ILD | RTD_4 | °C | 31.0 |
| Mass flow rate of inlet ILD | MassFlow_1 | g/s | 2.04 |
| Mass flow rate of outlet ILD | MassFlow_2 | g/s | 2.05 |
| Density of inlet ILD | FlowDensity_1 | $g/cm^3$ | 1.0819 |
| Density of outlet ILD | FlowDensity_2 | $g/cm^3$ | 1.0904 |
| Temperature of inlet air | T_Air_in | °C | 32.2 |
| Temperature of outlet air | T_Air_out | °C | 32.0 |
| RH of inlet air | RH_Air_in | % | 63.0 |
| RH of outlet air | RH_Air_out | % | 59.2 |
| Air flow rate | AirFlow | $m^3/h$ | 76.7 |

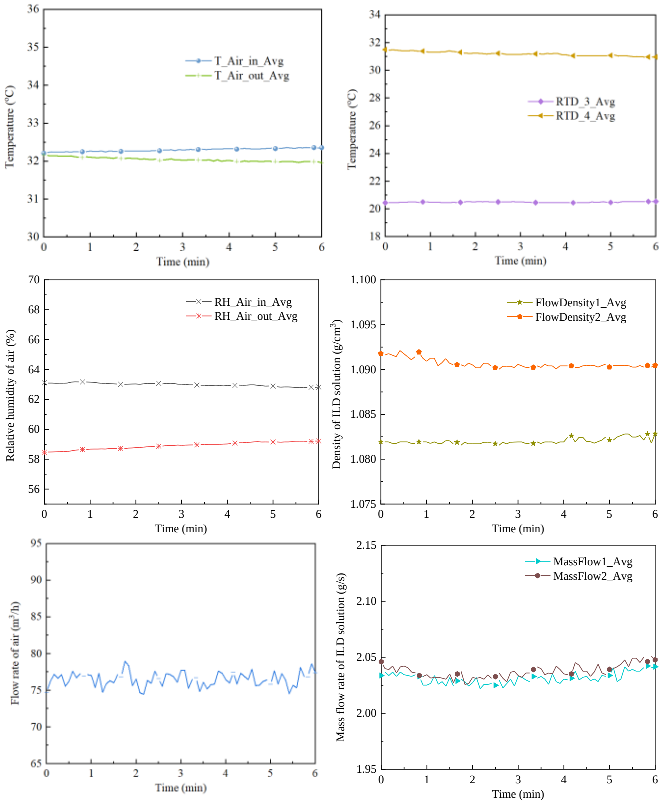


Fig. 3 Measured data during the test.

Table 3 shows the test results of various airflow rates ranged from 34.2-112 $m^3/h$ (Tests 1-3). The results are also compared graphically in Fig. 4. MRR was increased from 75.1 g/h to 180.3 g/h by increasing the airflow rate from 34.2 $m^3/h$ to 112 $m^3/h$. However, ε decreased from 12.7% to 9.3%. The reason why ε decreased with an increasing air flow rate is that the contact time between air and membrane becomes shorter when the air flow rate is higher, which results in insufficient water vapor separation from air to ILD solution through the membrane.

Fig. 5 shows that MRR increased from 55.8 g/h to 75.1 g/h and ε increased from 10.3% to 12.7% when the ILD solution flowrate was increased from 0.44 g/s to 2.13 g/s. The operating conditions of Tests 4-6 are listed in Table 4. Because air temperature was higher than that of the ILD solution and the dehumidification is an exothermic process, the ILD solution was warmed up in the dehumidifier, which

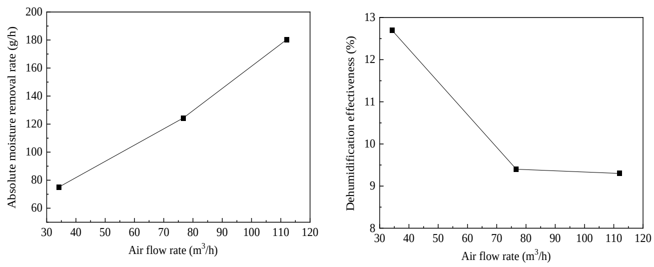


Fig. 4 Impacts of air flowrate on dehumidification performance.

TABLE 3. INFLUENCE OF AIR FLOW RATE ON THE DEHUMIDIFICATION PERFORMANCE.

| **Variable** | **Symbol** | **Unit** | **Test 1: ($m_a$=34.2$m^3$/h)** | **Test 2: ($m_a$=76.7$m^3$/h)** | **Test 3: ($m_a$=112$m^3$/h)** |
|---|---|---|---|---|---|
| Temperature of inlet ILD | RTD_3 | ºC | 21.0 | 20.5 | 21.0 |
| Temperature of outlet ILD | RTD_4 | ºC | 30.9 | 31.0 | 31.6 |
| Mass flow rate of inlet ILD | MassFlow_1 | g/s | 2.13 | 2.04 | 2.1 |
| Mass flow rate of outlet ILD | MassFlow_2 | g/s | 2.14 | 2.05 | 2.1 |
| Density of inlet ILD | FlowDensity_1 | g/$cm^3$ | 1.0817 | 1.0819 | 1.0786 |
| Density of outlet ILD | FlowDensity_2 | g/$cm^3$ | 1.0867 | 1.0904 | 1.0921 |
| Temperature of inlet air | T_Air_in | ºC | 32.4 | 32.2 | 32.2 |
| Temperature of outlet air | T_Air_out | ºC | 32.0 | 32.0 | 32.2 |
| RH of inlet air | RH_Air_in | % | 62.4 | 63.0 | 62.9 |
| RH of outlet air | RH_Air_out | % | 57.7 | 59.2 | 58.4 |
| Air flow rate | AirFlow | $m^3$/h | 34.2 | 76.7 | 112 |
| Moisture removal rate | MRR | g/h | 75.1 | 124.4 | 180.3 |
| Dehumidification effectiveness | ε | % | 12.7 | 9.4 | 9.3 |

TABLE 4. INFLUENCE OF ILD SOLUTION FLOW RATE ON THE DEHUMIDIFICATION PERFORMANCE.

| **Variable** | **Symbol** | **Unit** | **Test 4: ($m_s$=0.44 g/s)** | **Test 5: ($m_s$=1.11 g/s)** | **Test 6: ($m_s$=2.13 g/s)** |
|---|---|---|---|---|---|
| Temperature of inlet ILD | RTD_3 | ºC | 28.6 | 25.6 | 21.0 |
| Temperature of outlet ILD | RTD_4 | ºC | 31.8 | 31.4 | 30.9 |
| Mass flow rate of inlet ILD | MassFlow_1 | g/s | 0.44 | 1.11 | 2.13 |
| Mass flow rate of outlet ILD | MassFlow_2 | g/s | 0.44 | 1.11 | 2.14 |
| Density of inlet ILD | FlowDensity_1 | g/$cm^3$ | 1.0921 | 1.0869 | 1.0817 |
| Density of outlet ILD | FlowDensity_2 | g/$cm^3$ | 1.0903 | 1.0903 | 1.0867 |
| Temperature of inlet air | T_Air_in | ºC | 32.4 | 32.3 | 32.4 |
| Temperature of outlet air | T_Air_out | ºC | 32.2 | 31.9 | 32.0 |
| RH of inlet air | RH_Air_in | % | 63.0 | 63.1 | 62.4 |
| RH of outlet air | RH_Air_out | % | 59.2 | 59.6 | 57.7 |
| Air flow rate | AirFlow | $m^3$/h | 34.2 | 34.2 | 34.2 |
| Absolute moisture removal rate | MRR | g/h | 55.8 | 61.0 | 75.1 |
| Dehumidification effectiveness | ε | % | 10.3 | 11.3 | 12.7 |

resulted in elevated equilibrium water vapor pressure of the ILD solution and thus reduced the driving force of the dehumidification process. Increasing ILD solution flowrate can help mitigate the temperature rise of the ILD solution and thus improve MRR and ε of the dehumidifier.

## IV. CONCLUSIONS

To eliminate carryover and contamination problems, a new membrane-based dehumidifier was developed. It is comprised of a bundle of small diameter tubes made with thin nonporous membrane, which has high water vapor permeability (a variance of the PFSA membrane). It also uses an ionic liquid ([EMIM][OAc]) as desiccant, which is non-corrosive to metals and non-crystallizable. Dehumidification performance of a benchtop protype of this new dehumidifier was tested under various operating conditions. Test results indicate that the prototype can effectively dehumidify air with a latent effectiveness up to 13% and a MMR up to 180 g/h.

Flowrates of the ILD solution and the air significantly affect the dehumidification performance. Increasing airflow can increase MMR but reduce latent effectiveness. Increasing ILD solution flow can increase both the MMR and the latent effectiveness. However, a higher ILD flowrate will increase the pressure drop across the membrane tubes and could even break the membrane tubes and result in leakage of the ILD solution.

Increasing the length of the membrane tube and the airflow disturbances in the dehumidifier has potential to improve dehumidification performance and thus is recommended for further study.

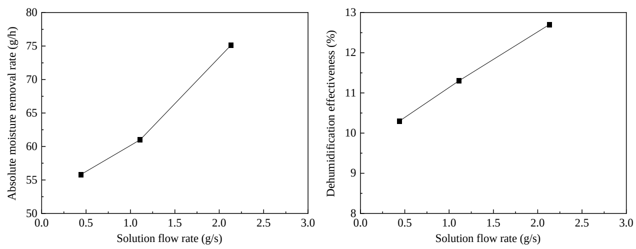


Fig. 5 Impacts of ILD solution flowrate on dehumidification performance.

## Acknowledgment

This work was funded by the Emerging Technologies Program of the Buildings Technology Office at the US Department of Energy; Xergy, a small business technology inventor is the industrial partner of this project. This work has been authored by staff of UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the US Department of Energy (DOE). The US government retains and the publisher, by accepting the presentation for publication, acknowledges that the US government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this presentation, or allow others to do so, for US government purposes. DOE will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

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