Design and experiment study of membrane based isothermal dehumidifier in HVAC system

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Abstract. As passive building systems improve, sensible loads decrease and the air conditioning system takes on a greater role in dehumidification. Isothermal dehumidifier with membrane, which utilizes a vacuum pump to create a partial vapor gradient between membranes, has the potential to save significant energy by operating just for latent cooling as a thermally decoupled system. Although research has concentrated on analyzing the dehumidification and energy performance of isothermal dehumidifiers via simulation studies, their design and experimental analysis for dehumidification systems in HVAC systems remain rare. In this study, we constructed a prototype of an isothermal dehumidifier using hollow fiber membrane modules and vacuum pumps for an air conditioning system. Under different air conditions, the constructed prototype was evaluated for dehumidification characteristics (i.e., isothermal process, moisture removal rate, and dehumidification efficacy). Three factors were used to choose the air conditions for testing the dehumidification performance: air temperature, air humidity, and air velocity. The experiment results indicated that the isothermal dehumidifier dried the air without changing the temperature, and the overall dehumidification performance of the prototype system indicated that the humidity ratio difference was between 3.8 and 14 g/kg, the moisture removal rate was between 0.12 and 1.0 kg/h, and the dehumidification effectiveness was between 36% and 81%.

Keywords. Isothermal dehumidifier, dehumidification performance, Experiment study
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1. Introduction

A cooling coil is used in an air conditioning system to dehumidify the air through a condensation process [1]. The method can result in significant energy usage due to excessive dehumidification cooling and air pollution issues due to the wet coil [2]. Desiccant systems, such as desiccant wheels and liquid desiccant systems, are an alternative dehumidification system; however, without a free heat source (e.g., solar thermal or waste heat source), the regeneration process to maintain the dehumidification performance of the systems consumes a significant amount of energy [3].

A vacuum-based membrane dehumidifier has been suggested as a more thermally efficient dehumidification approach than traditional dehumidification systems [4, 5]. The system utilizes gas separation technology that is entirely dependent on the difference in partial vapor pressure between the membranes. A vacuum pump depressurizing the humid air permeates the water vapor in the air via the membrane layer, and then dry air is provided.

The vacuum-based membrane dehumidifier's dehumidification and energy performance are calculated using many impacted parameters: feed air velocity, feed air humidity ratio, water vapor permeability, selectivity, and vacuum pressure. The primary factors that have an influence on the system's dehumidification performance are the membrane selectivity and permeance of the material qualities, as well as the vacuum pressure of the operating energy used to depressurize the vacuum side. Thuan et al. [6] shown that the vacuum-based membrane dehumidifier's theoretical coefficient of performance (COP) is between 2 and 3 under isentropic vacuum pump conditions and infinite selectivity. El-Dessouky et al. [7] suggested a system that combines air conditioning with a vacuum-based membrane dehumidifier. The proposed system is a decoupled air conditioning system that utilizes a vacuum-based membrane dehumidifier for latent cooling and an indirect/direct evaporative cooler for sensible cooling. The simulation findings indicate that the suggested system, which incorporates a vacuum-based membrane dehumidifier, may save up to 86 percent of the energy used by a standard air conditioning system.

Although previous research has primarily used numerical methods or simulations to estimate the dehumidification and energy performance of vacuum-based membrane systems, experimental analysis of vacuum-based membrane dehumidifiers operating in a variety of air conditions for HVAC systems is extremely rare. We developed a prototype of a vacuum-based membrane dehumidifier for use in an air conditioning system and assessed its dehumidification performance under a variety of settings in this work. A series of experimental data was used to determine the sensitivity of the operating condition on the dehumidification performance of the vacuum-based membrane dehumidifier.

2. Membrane based isothermal dehumidifier

2.1 System overview

As seen in Figure 1, a vacuum-based membrane dehumidifier (VMD) is composed of membrane modules and a vacuum pump. The membrane modules are composed of thick hollow fiber membranes constructed of polymeric materials with a high selectivity and permeability for water vapor. The water vapor in the humid air (i.e., feed side) penetrates to the vacuum side (i.e., permeate side) of the VMD system through the membrane layer due to the partial vapor pressure difference between the membranes. To provide the partial vapor pressure gradient that serves as the dehumidification's driving power, the vacuum pump depressurizes the permeate side to practically vacuum pressure.

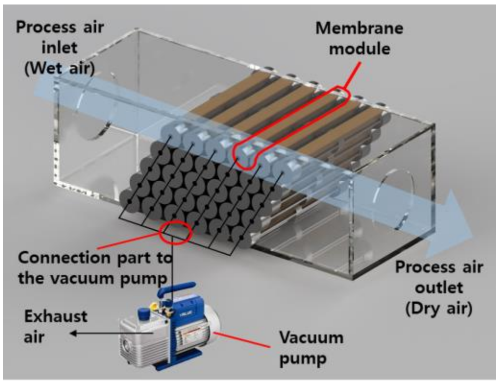


Fig. 1 – Configuration of the vacuum-based membrane dehumidification system

Figure 2 illustrates the VMD's dehumidification procedure in detail. When the system makes advantage of the highly selective and permeance of water vapor to generate a partial vapor pressure difference between the feed and permeate sides, the water vapor with a high chemical potential on the feed side adsorbs to the membrane surface layer. The adsorbed water vapor then diffuses through the membrane and desorption occurs on the permeate side.

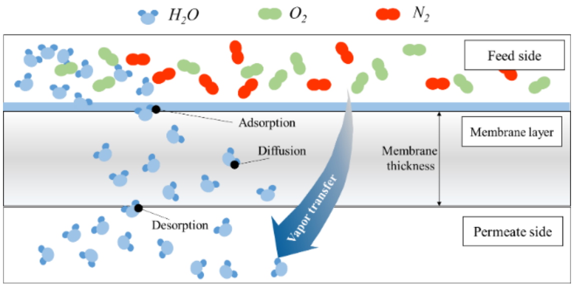


Fig. 2 – Dehumidification process of the vacuum-based membrane dehumidifier

3. Experiment overview

3.1 Experiment setup

The experimental setup for the vacuum-based membrane dehumidifier is shown in Figure 3. The process air is supplied to the shell side of the hollow fiber in the membrane module, while the vacuum pressure depressurizes the permeate side, which is also the shell side of the hollow fiber. Mass transfer happens through the isothermal process in the dehumidification process. The environmental chamber conditions the air entering the VMD system in order to maintain the desired air temperature and humidity ratio.

A variable fan installed on the exhaust side was used to manage the flow rate of the process air. The permeate side vacuum pressure was maintained near vacuum (e.g., 3.3 kPa) using a 1.4 kW commercial vacuum pump. To test the VMD system's dehumidification performance, we examined the inlet/outlet air temperature and humidity, as well as the permeate side vacuum pressure.

Figure 3 depicts the actual experimental setup for the dehumidification test using the vacuum-based membrane dehumidifier. The membrane modules are cylindrical in shape and measure 360 mm in length and 55 mm in diameter. The modules are made of a dense form of hollow fiber membranes 400 µm in diameter. We constructed a complete system of the VMD using 24 membrane modules. To determine the inlet and outflow air conditions, air temperature and humidity sensors with insulation were put at the system's intake and outlet. The variable fan is used to distribute process air in the feed side of the membrane modules, and the airflow rate of the process air is recorded at the system's input by a flowmeter. The permeate side vacuum pressure was determined using a digital pressure sensor connected to the vacuum pump. Each experiment lasted 10 minutes after the system reached steady-state, and data from the sensors were gathered at 1-second intervals to the data recorders. The measuring equipment's ranges and accuracies are reported in Table 1.

Tab. 1 – Sensor characteristics

Variable	Sensor type	Range	Accuracy
Air temperature and relative humidity	Temperature/humidity probe	Temperature: -20 to 60 °C Humidity: 0 to 100%	±0.5 °C ±1.8 %
Air velocity	Vane probe	0.1 to 15 m/s	± 0.1 m/s

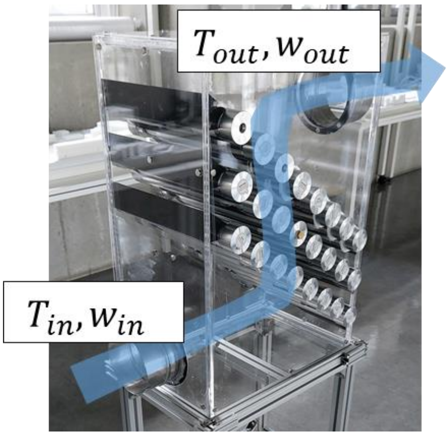


Fig. 3 – Experimental setup of vacuum-based membrane dehumidifier

To conduct the parametric analysis experiments, we evaluated three operational factors that impact the VMD system's dehumidification performance: the air temperature, the humidity ratio, and the air flow rate. In the local standard for a desiccant dehumidifier test condition, the experimental design for the parametric analysis was examined. The VMD was used to perform parametric analysis on five air conditions, with the input temperature set to 25°C to 33°C and the humidity ratio set to 15.96 g/kg to 25.74 g/kg, respectively. The input airflow rate was varied between 18 and 112.5 m^3/h on a four-level basis, while the permeate side vacuum pressure was maintained at 3.3 kPa. Table 2 summarizes the detailed test conditions for the parametric study.

Tab. 2 – Test condition for parametric study

Point	Temperature (°C)	Humidity ratio (g/kg)	Air flow rate (m^3/h)
P1-1	33	25.74	18
P1-2	33	25.74	37.5
P1-3	33	25.74	75
P1-4	33	25.74	120
P2-1	33	20.85	18
P2-2	33	20.85	37.5
P2-3	33	20.85	75
P2-4	33	20.85	120
P3-1	33	15.96	18
P3-2	33	15.96	37.5
P3-3	33	15.96	75
P3-4	33	15.96	120
P4-1	29	20.85	18
P4-2	29	20.85	37.5
P4-3	29	20.85	75
P4-4	29	20.85	120
P5-1	25	20.85	18
P5-2	25	20.85	37.5
P5-3	25	20.85	75
P5-4	25	20.85	120

2.2 Performance index

The humidity ratio difference, moisture removal rate, and dehumidification effectiveness of the VMD system were used as performance indicators for dehumidification. The difference in humidity ratios is defined as the difference between the intake and outlet air humidity ratios (Eq. (1)), which indicates the change in the outlet air state. The moisture removal rate is defined as the process air's dehumidification mass flow rate (Eq. (2)), and the dehumidification effectiveness is defined as the ratio of the water vapor's actual mass flow rate to its maximum mass flow rate (Eq. (3)).

$$\Delta w = w_{f,in} - w_{f,out} \quad (1)$$

$$\dot{m}_d = \dot{m}_a \Delta w \quad (2)$$

$$\varepsilon_d = \frac{\dot{m}_{v,real}}{\dot{m}_{v,max}} = \frac{w_{f,in} - w_{f,out}}{w_{f,in} - w_{eq}} \quad (3)$$

To measure the dehumidification effectiveness, the maximum mass flow rate of water vapor is estimated using Eq (4). The equilibrium humidity ratio is established by the permeate side partial vapor pressure, which is determined by the feed side air conditions (i.e., mass transfer NTU, feed side vacuum pressure, and permeate side partial vapor pressure), as well as the feed side membrane parameters (selectivity, and permeance) as determined by Eq (5).

$$w_{eq} = 0.62198 \frac{P_{p,v,o}}{P_{total} - P_{p,v,o}} \quad (4)$$

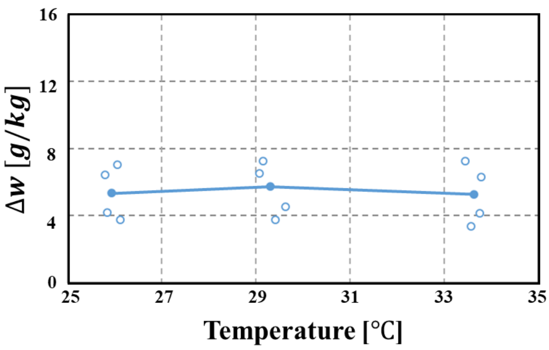
$$P_{p,v,o} = f(P_{f,v,i}, NTU_m, P_{p,t}, \text{Sel}, \text{Per}) \qquad (5)$$

4. Experiment results

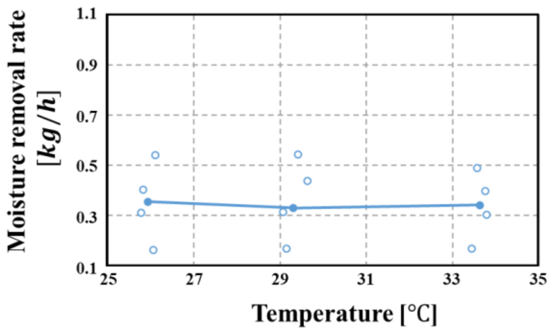
4.1 Temperature

Figure 4 illustrates the effect of air temperature on the dehumidification performance of a vacuum-based membrane dehumidifier. P2, P4, and P5 were the 14 test point sets, which all had the same humidity ratio (i.e., 20.85 g/kg) but with varying airflow speeds. The results indicate that the humidity ratio difference was between 3.8 and 7 g/kg, the moisture removal rate was between 0.12 and 0.55 kg/h, and the dehumidification effectiveness was between 36% and 81%. The parametric study demonstrates that air temperature has no noticeable impact on the difference in humidity ratios and the rate of moisture removal. Increases in the air temperature of the VMD system improve the water vapour permanence of the membrane. However, it had a lesser effect on dehumidification effectiveness owing to fluctuations in the under-air conditioning system's air temperature.

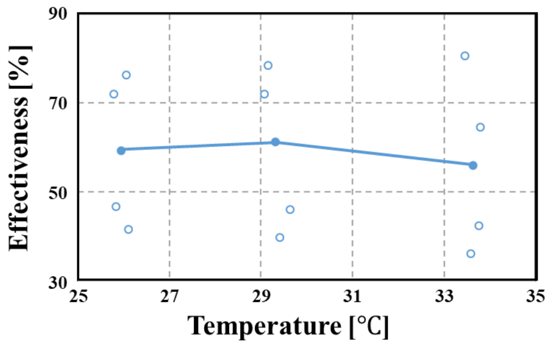
Figure 4.c illustrates the impact of air temperature on the VMD system's dehumidification effectiveness. Additionally, no substantial effect of air temperature is shown, because the driving force of mass transfer, which is the partial vapor pressure between the membrane feed and permeates sides, is unaffected by air temperature.



(a) Humidity ratio difference



(b) Moisture removal rate



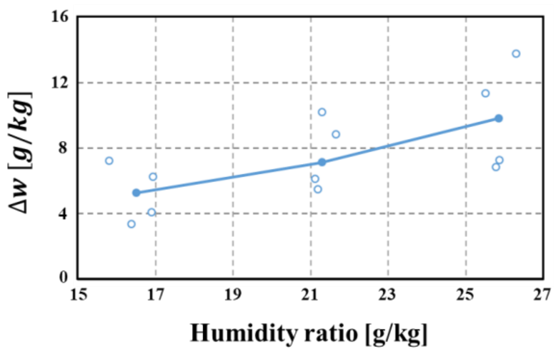
(c) Effectiveness

Fig. 4 - Influence of process air temperature

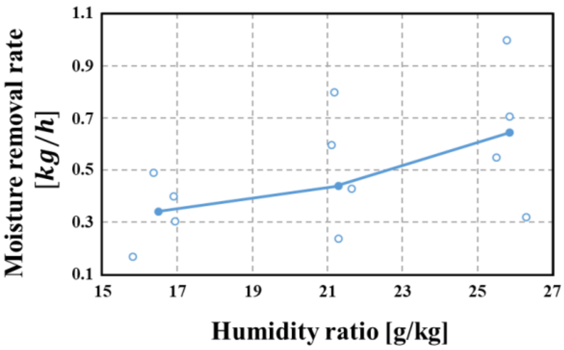
4.2 Humidity ratio

Figure 5 illustrates the effect of the air humidity ratio on the dehumidification performance of a vacuum-based membrane dehumidifier. P1, P2, and P3 were the 14 test point sets, which all had the same temperature (33°C) but with varying airflow speeds. The findings indicate that the humidity ratio difference was between 3.8 and 14 g/kg, the moisture removal rate was between 0.12 and 1.0 kg/h, and the dehumidification effectiveness was between 36% and 81%. The parametric study shows that the humidity ratio has a significant effect on the humidity ratio difference and moisture removal rate, as the partial vapor pressure difference between the membrane feed and permeate side increases, increasing the VMD system's process air humidity ratio.

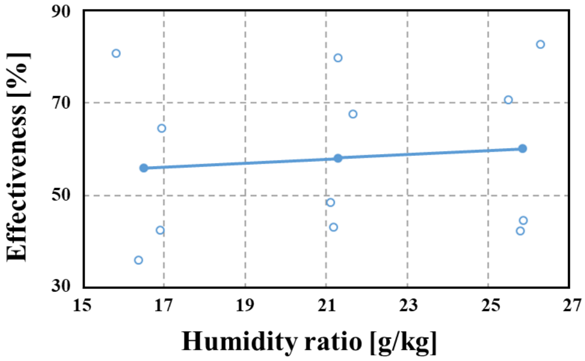
Figure 5.c illustrates the impact of airflow rate on the dehumidification effectiveness. The results indicate that there is a less significant effect on the air humidity ratio (positive correlation). Even though the driving force of mass transfer was increased with an increase in the humidity rate, the mass NTU, which is a factor of the permeate flow rate across the membrane, remained unchanged.



(a) – Humidity ratio difference



(b) Moisture removal rate



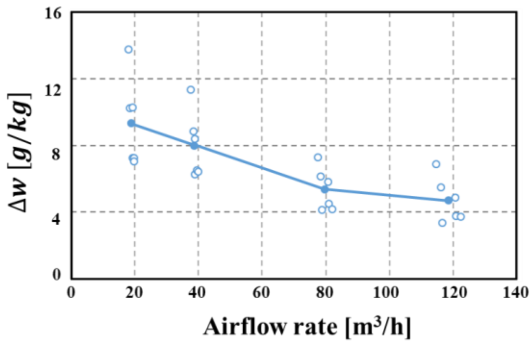
(c) Effectiveness

Fig. 5 - Influence of process air humidity ratio

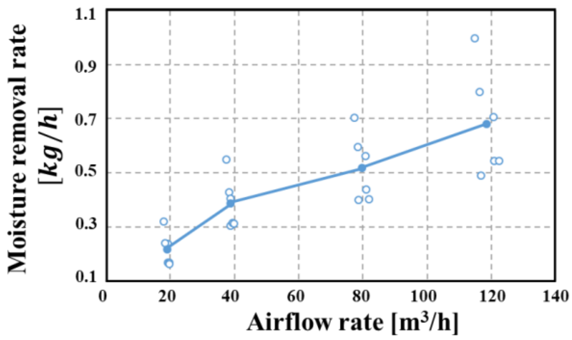
4.3 Flow rate

Figure 6 illustrates the effect of airflow rate on the dehumidification performance of a vacuum-based membrane dehumidifier. The 24 test point sets were classified as P1–P6, and the data set was organized according to airflow rate. The findings indicate that the humidity ratio difference was between 3.8 and 14 g/kg, the moisture removal rate was between 0.12 and 1.0 kg/h, and the dehumidification effectiveness was between 36% and 81%. The parametric study demonstrates that the humidity ratio has a large negative influence on the difference in humidity ratios owing to the reduction in mass NTU, which increases the airflow rate. The effect of the moisture removal rate, on the other hand, is positive since the impact of decreasing the mass NTU is less than the impact of increasing the airflow rate, as indicated in Eq (2).

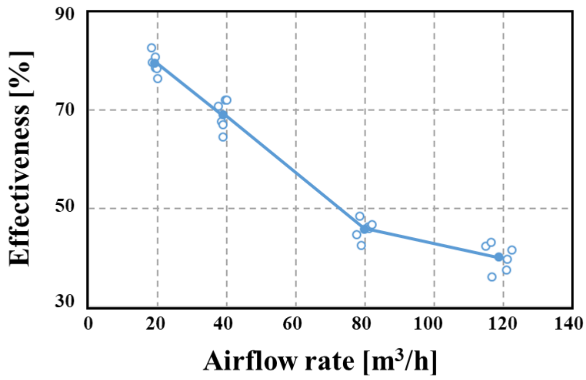
Figure 6.c illustrates the impact of airflow rate on the VMD system's dehumidification effectiveness. The data indicate that the greatest negative impact is on the air humidity ratio. Because the mass NTU is inversely proportional to the airflow rate, increasing the airflow rate results in a reduction in the VMD system's dehumidification effectiveness.



(a) Humidity ratio difference



(b) Moisture removal rate



(c) Effectiveness

Fig. 6 - Influence of process airflow rate

In short, air temperature has no influence on dehumidification performance (humidity ratio difference, moisture removal rate, and dehumidification effectiveness). The humidity ratio and airflow rate are the two variables that have the greatest influence on the amount of moisture removal rate. Because variations in the humidity rate correspond to variations in the driving force of mass transfer, while variations in airflow correspond to variations in mass NTU. Additionally, the mass NTU as a function of the change in airflow rate was shown to be the most significant factor affecting the effectiveness.

5. Conclusion

The purpose of this work was to conduct an experimental evaluation of the vacuum-based membrane dehumidifier's dehumidification performance using parametric analysis and to construct an empirical model of dehumidification effectiveness. A series of studies were done in a controlled setting with varying operating conditions. The humidity ratio difference, moisture removal rate, and dehumidification effectiveness were used to evaluate the vacuum-based membrane dehumidifier's performance. On the basis of an experimental design, a parametric study of the vacuum-based membrane dehumidifier was conducted.

According to the testing findings, the overall dehumidification performance of the prototype system was between 3.8 and 14 g/kg, the moisture removal rate was between 0.12 and 1.0 kg/h, and the dehumidification effectiveness was between 36% and 81%, respectively. The parametric study revealed that the inlet humidity ratio and airflow rate had a significant effect on the dehumidification performance of the humidity ratio difference and moisture removal rate. The airflow rate was the primary affect parameter for dehumidification effectiveness. This experimental results demonstrate application to a dehumidifying device (dedicated outdoor air system or air conditioning system) for indoor latent heat removal as a thermally decoupled air conditioning system by demonstrating that isothermal dehumidification is feasible.

6. Acknowledgement

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