Experimental investigation on a packaged unit of membrane dehumidification-based ventilation system

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Abstract. This study purposed to experimentally investigate the seasonal operating performance of the packaged unit of a hollow membrane-based ventilation system. The packaged unit of the proposed ventilation system was fabricated, and the experiments was conducted based on the test standards for the energy recovery ventilator addressed from air-conditioning, heating and refrigeration institute (AHRI). In addition, for achieving the optimal heat and moisture recovery from the ventilation system under various operating conditions, the seasonal operation modes were suggested for the packaged unit of the proposed ventilation system. The measured data showed that the proposed ventilation unit can provide the ventilation air ait nearly neutral air temperature and humidity ratio in each operation mode. In addition, the average sensible effectiveness, the average latent effectiveness, and the average enthalpy effectiveness of the proposed ventilation system are 70.7%, 75.9%, and 75.6% in mode 1; 44.4%, 74.7%, 80.2% in mode 2; 77.6%, 70.4%, 85.6% in mode 3, which exhibited the higher heat and moisture recovery performance compared to the commercial energy recovery ventilator. In conclusions, the measured data demonstrates that the proposed ventilation system has a great application potential for building ventilation unit in terms of energy recovery performance.

Keywords. Packed-ventilation system, hollow fiber membrane, dehumidification, experiment.
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1. Introduction

Recently, net zero energy buildings, which refer to a building with zero-net energy consumption over a typical year, have emerged as buzzwords in heating, ventilation, and air-conditioning (HVAC) research field. To realize net zero energy buildings, there has been many approaches in building design such as the increase in building insulation and airtightness levels. The well-insulated buildings have reduced the total building thermal load, particularly, the sensible cooling load. On the other hand, the buildings with high airtightness level requires higher mechanical ventilation loads for maintaining satisfactory indoor air quality and occupant comfort, which could lead to higher energy consumption in space-air conditioning. Therefore, the demands for energy efficient ventilation systems are growing in building application fields.

Energy recovery ventilators (ERVs), which are widely used in HVAC system, utilize the waste heat and moisture within the exhausted room air instead of releasing it directly to the outsides. Commercial ERVs, which are typically composed of flat sheet hydrophilic polymer, exhibit 50–80% of sensible heat exchange effectiveness and 20–60% of latent heat exchange effectiveness [1]; that is, the latent effectiveness of the commercial ERV is lower than the sensible effectiveness. Therefore, applying an energy recovery ventilation system with high latent cooling efficiency is indispensable to reduce the energy consumption of buildings in hot and humid regions.

Therefore, previous studies have proposed hollow fiber membrane dehumidification-based dual core ventilation system, and evaluated the applicability of the proposed system in HVAC applications via theoretical and experimental approaches. Cho et al. [2] has explored the application potential of a hollow fiber membrane-based latent heat exchanger via experimental approach, and their results showed that the proposed latent heat exchanger exhibits superior latent cooling performance rather than sensible cooling owing to its hollow fiber structure, and exhibits 35.3–82.7% of latent cooling effectiveness. Cho et al. [3] also fabricated a mock-up model of hollow fiber membrane based latent heat exchange module for developing regression models for predicting its latent heat exchange performance under various outdoor air conditions. Then, a series of energy simulations was performed to assess annual energy saving potentials of the proposed ventilation unit compared with the conventional ERV unit [4]. Their results showed that the proposed ventilation unit reduced of 59.7% of ventilation load and conserved 24% of primary energy consumption in space cooling owing to its higher latent cooling effectiveness and selective heat and moisture reclaims from sensible/latent heat exchange dual core systems.

Subsequently, in this study, a pilot unit of the proposed ventilation unit was constructed, and transient operating behaviours and characteristics were experimentally evaluated.

2. System overview

As shown in Figure 1, the proposed ventilation unit consists of a hollow fiber membrane-based latent heat exchanger (M-LHX) and the sensible heat exchanger (SHX). When the fresh outdoor air (OA) enters the primary inlet air channel and the exhausted room air (RA) enters the secondary inlet air channel, the M-LHX initially reclaims the latent heat from the RA leaving the SHX, and the SHX recovers the sensible heat from RA upstream of SHX.

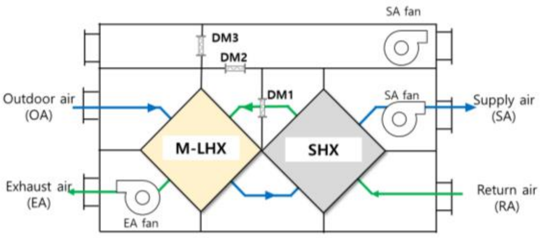

Fig. 1 – Schematic of a proposed packaged ventilation unit

As can be seen in Figure 2, the operating modes of the proposed system are classified into four modes based on OA conditions: the total heat exchange modes (Region 1, 3), the latent heat exchange in cooling seasons (Region 2), and the by-pass mode (Region 4). When the temperature and humidity ratio of OA are higher than those of the room air (RA) or lower than those of the design supply air (i.e., 15 ºC), the M-LHX initially recovers the latent heat from the RA downstream of the SHX. Then, the SHX reclaims the sensible heat from RA. If the temperature of the OA is lower and the humidity ratio of the OA is higher than those of RA, the proposed system operates in latent exchange mode for preventing unnecessary heat exchange from RA. The introduced OA is dehumidified by exchanging moisture with the RA, while the SHX is bypassed. In a sensible exchange mode, when the humidity ratio of the OA is lower and the temperature of the OA is higher than that of the RA, the introduced OA only passes the SHX, and the M-LHX is bypassed. When the temperature and humidity ratio of the OA are lower than that of the RA both the temperature of OA is higher than the design supply air temperature, the bypass mode is activated.

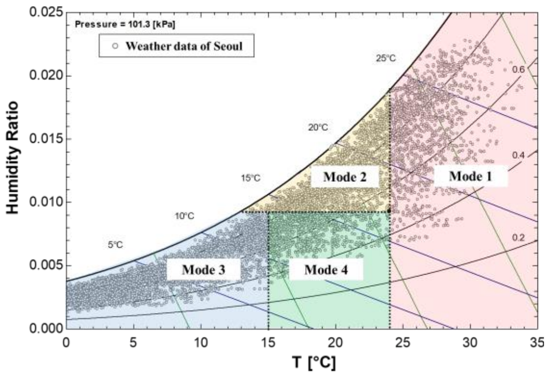

Fig. 2 – Operation modes according to outdoor air conditions on psychrometric chart

3. Experimental overview

3.1 Experiment set up

Figure 3 shows the experimental setup for the pilot unit of the proposed ventilation system. The primary produced by the environmental chamber is blown to the M-LHX facing the tube side, whereas the secondary air is supplied to the SHX. The heat and mass transfer occurs in the primary air and secondary air directions. Polyethersulfone (PES) coated with a hydrophilic polymer was selected as the material for the M-LHX, and the stainless and aluminium are selected as plate and frame material in SHX. The dimensions of the M-LHX and SHX are determined based on the design flow rate of the supply air as 150 m^3/h. Detailed physical information of the proposed ventilation unit fabricated in this study is summarized in Table 1.

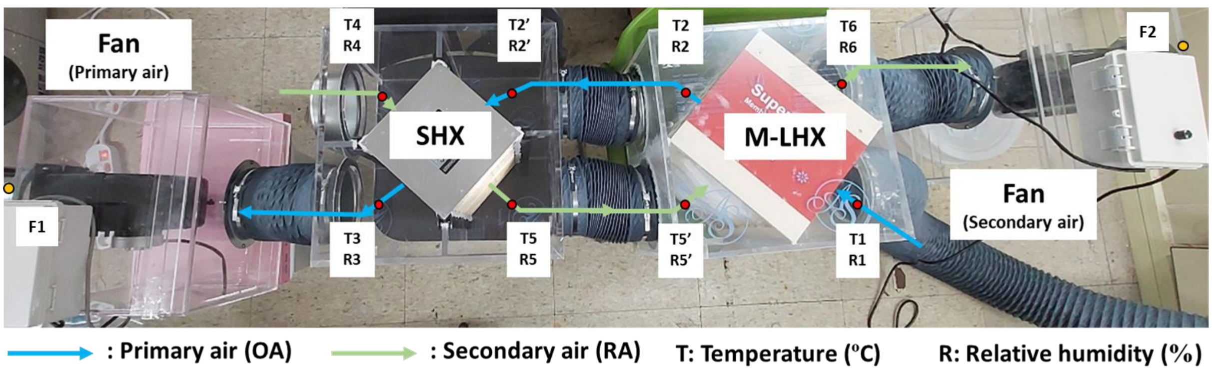

Fig. 3 – Photograph of experimental setup of the proposed ventilation unit

Tab. 1 – Physical information of M-LHX and SHX in the proposed system

Description		Contents
M-LHX	material	polyethersulfone with 9 wt.% of polyvinyl-pyrrolidone
	dimensions	280 mm (W) × 280 mm (D) × 350 mm (H)
SHX	material	Aluminium / stainless
	dimensions	250 mm (W) × 250 mm (D) × 350 mm (H)

3.2 Test conditions

In this study, to investigate the operating performance and feasibility of the proposed system, the transient operating behaviours and characteristics of the critical operating parameters were monitored and for each operating mode 1,2, and 3. The inlet primary air temperature ($T_{a,pri,in}$), the inlet primary air relative humidity ($Rh_{a,pri,in}$), the inlet secondary air temperature ($T_{a,sec,in}$), and the inlet secondary air relative humidity ($Rh_{a,sec,in}$) were selected as four operating parameters. The conditions of the primary air for each mode were determined according to local standard of KS B 6879 heat recovery ventilators [1]. The secondary air conditions for each mode were determined according to the recommend indoor air conditions for cooling and heating seasons. Considering the minimum ventilation rate for a residential or office building with 100 m^2 of floor area, the air flow rate of the primary air and secondary air was set to 150 m^3/h. Table 2 summarized the test conditions for each operation mode. All experiments were conducted in laboratory scale at least 30 minutes.

Tab. 2 – Test conditions for each mode

Mode	Primary air conditions		Secondary air conditions	
	Temp. [ºC]	Relative humidity [%]	Temp. [ºC]	Relative humidity [%]
1	28	72.5	24	50
2	22	72	24	50
3	9	30	20	50

3.3 Performance indices

As performance indices representing the operating performance of the proposed ventilation unit, the sensible heat exchange effectiveness (ε_s), which is defined as the ratio of the temperature variation of the primary air to the theoretical maximum temperature variation (equation 1), the latent heat exchange effectiveness (ε_l), which is defined as the ratio of the humidity ratio variation of the primary air to the theoretical maximum humidity ratio variation (equation 2), and the enthalpy exchange effectiveness(ε_h), which is defined as the ratio of the enthalpy variation of the primary air to the theoretical maximum enthalpy variation (equation 3), were selected.

$$\varepsilon_s = \frac{T_1 - T_3}{T_1 - T_4} \quad (1)$$

$$\varepsilon_l = \frac{\omega_1 - \omega_3}{\omega_1 - \omega_4} \quad (2)$$

$$\varepsilon_h = \frac{h_1 - h_3}{h_1 - h_4} \quad (3)$$

To obtain those three performance indices in each experiment, the inlet primary air temperature (T_1), the inlet primary air relative humidity (R_1), the outlet primary air temperature (T_3), the outlet primary air relative humidity (R_3), the inlet secondary air temperature (T_4), the inlet secondary air relative humidity (R_4) were measured. To respectively assess the operating performance of M-LHX and SHX, the temperature and relative humidity of the primary air downstream of the M-LHX (T_2 and R_2), those of the secondary air downstream of the SHX (T_5 and R_5) were also measured. listed in Table 3, commercial hygrometers were installed at each measuring point for obtaining the temperature and relative humidity of inlet and outlet air conditions. The air flow rate of the primary air (F_1) and the secondary air (F_2) were measured by installing the vane probes downstream of the primary air and secondary air, respectively.

Tab. 3 – Sensor characteristics.

Variable	Sensor type	Range	Accuracy
Temp. /humid.	Thermal hygrometer	-20–60 ºC (Temp.)	±0.5 °C (Temp.)
		0–100% (Humid.)	±1.8% (Humid.)
Air velocity	Vane probe	0.1–15 m/s	± 0.1 m/s

4. Results and discussions

4.1 Uncertainty analysis

Uncertainty analysis was performed for each measured parameter based on ASHRAE guidelines [5]. The overall uncertainty for each variable (U_y) was estimated using equation 4, with the propagated error (B_y), and the random error (P_y). The propagated error was obtained using the fixed error for each variable (b_{x_i}), which can be calculated by multiplying the sensor error and the standard deviation of the measured data (equation 5). The random error was estimated by equation 6 using the standard deviation of the measured data. The overall uncertainty values of the measured inlet and outlet parameters for each mode are listed in Table 4.

$$U_y = ({B_y}^2 + {P_y}^2)^{1/2} \quad (4)$$

$$B_y = [\sum_{i=1}^{n}(\frac{dy}{dx_i}b_{x_i})^2]^{1/2} \quad (5)$$

$$P_y = \frac{2S_r}{\sqrt{M}} \quad (6)$$

Tab. 4 – Overall uncertainty

Overall uncertainty of measured parameter [%]			
Measuring parameters	Operating mode		
	1	2	3
T_1	1.29	2.26	1.67
R_1	5.13	7.69	4.56
T_2	0.45	2.42	1.56
R_2	4.21	6.45	4.78
T_3	1.84	2.74	2.08
R_3	5.54	7.16	4.65
T_4	0.45	5.35	1.09
R_4	1.74	6.87	4.23
T_5	1.62	5.74	2.24
R_5	3.12	6.38	6.51
F_1	0.77	0.85	0.74
F_2	0.64	0.66	0.71

4.2 Operating characteristics

4.2.1 Operating mode 1

Figure 4 presents the experimental results for the temperature and humidity behaviours of the air flows for operation mode 1. Owing to heat and moisture exchange between the introduced secondary air from the M-LHX, the inlet primary air (28.3 ºC, 19.3 g/kg) was cooled to an average of 27.9ºC, and dehumidified to an average of 11 g/kg when the 23.8 ºC, 8.26 g/kg of the secondary air was introduced. In addition, the primary air entering the SHX was cooled to an average of 25 ºC and maintained 10.8 g/kg of humidity ratio. This results indicate that the proposed ventilation unit could supply the ventilation air at nearly neutral air temperature and humidity ratio by recovering sufficient amount of sensible and latent heat from the secondary air. In addition, one can see that the proposed ventilation unit could provide decoupled heat and moisture recovery performance from M-LHX and SHX.

In terms of the heat and moisture recovery performance, the sensible effectiveness, latent effectiveness, and the enthalpy effectiveness respectively ranged 65–74.4%, 70.3–81.5%, and 72.8–78.3%. Particularly, one can see that the proposed ventilation unit exhibits higher latent effectiveness compared with the commercial ERV (30–60%) from the M-LHX.

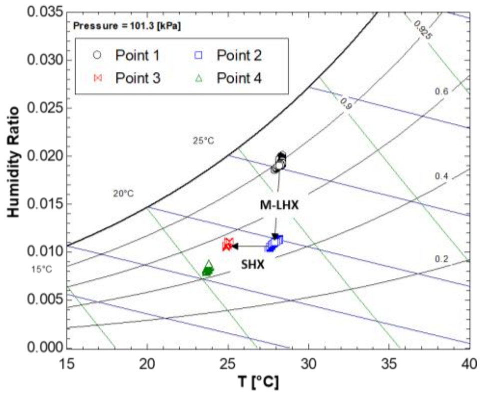

Fig. 4 – Temperature and humidity behaviours of air flows for mode 1

4.2.2 Operating mode 2

Figure 5 presents the experimental results for the temperature and humidity behaviours of the air flows for operation mode 2. The inlet primary air (20.9 ºC, 12.6 g/kg) was dehumidified by M-LHX to an average of 10.2 g/kg, but occurs slight temperature increase to an average of 22.3 ºC when the 24 ºC, 8.96 g/kg of the secondary air was introduced.

The sensible effectiveness, the latent effectiveness, and the enthalpy effectiveness ranged 40.6–48.2%, 70.7–78.6%, and 77.6–82.8%. This results indicate that the proposed ventilation unit could provide satisfactory latent cooling performance, and minimize unnecessary heat exchange with RA only by entering M-LHX.

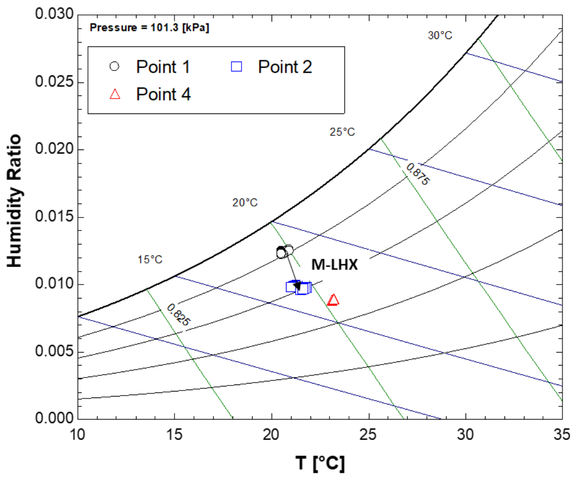

Fig. 5 – Temperature and humidity behaviours of air flows for mode 2

4.2.2 Operating mode 3

Figure 6 presents the temperature and humidity behaviours of the air flows for operation mode 3. The inlet primary air (9.1 ºC, 2.8 g/kg) was initially heated and humidified by M-LHX to an average of 14.3 ºC and an average of 4.75 g/kg when the inlet secondary air is 20 ºCm 6.67 g/kg. Then, the SHX heated the primary air to an average of 18.6 ºC.

The sensible effectiveness, the latent effectiveness, and the enthalpy effectiveness ranged 71.2–80%, 65.3–73.5%, and 84.4–86.8%. This results indicate that the proposed ventilation unit showed relatively lower latent effectiveness compared with the operation mode in cooling seasons, but the proposed unit showed enhanced sensible and latent heating effectiveness compared with the conventional ERV.

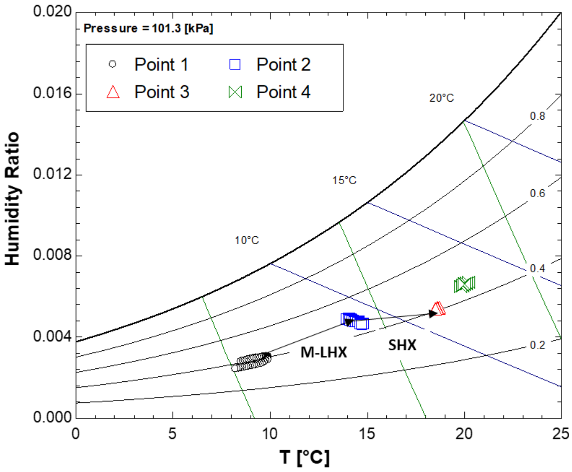

Fig. 6 – Temperature and humidity behaviours of air flows for mode 2

5. Conclusions

This paper experimentally investigated the seasonal operating performance of the packaged unit of a membrane-based ventilation system. The packaged unit of the proposed ventilation system was fabricated, and the experiments was conducted based on the test standards for the energy recovery ventilator addressed from air-conditioning, heating and refrigeration institute (AHRI). In addition, for achieving the optimal heat and moisture recovery from the ventilation system under various operating conditions, the seasonal operation modes were suggested.

The experimental results showed reliable air temperature and humidity behaviors that correspond to the inlet primary and secondary air conditions. In addition, the average sensible effectiveness, the average latent effectiveness, and the average enthalpy effectiveness of the proposed ventilation system are 70.7%, 75.9%, and 75.6% in mode 1; 44.4%, 74.7%, 80.2% in mode 2; 77.6%, 70.4%, 85.6% in mode 3. This indicates that the proposed ventilation system showed higher heat and moisture recovery performance compared with the commercial ERV during annual operation owing to its higher latent heat recovery performance from M-LHX and its selective operation strategies based on OA conditions.

Consequently, this study showed that the proposed ventilation unit has energy saving potential in HVAC application in terms of its energy recovery performance. However, further study should evaluate its fan energy for considering the energy efficiency of the proposed ventilation unit.

6. Acknowledgement

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7. References

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