Humidification Performance Evaluation of hollow-fiber membrane-based humidifier for air-conditioning

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Abstract. Indoor viral and fungal activity is affected by the concentration of moisture in the air. Since the concentration of viruses and fungi in the air directly affects the human body, it is necessary to maintain a specific humidity range through the air-conditioning system. The optimum humidity in the building is 40-60%, and it needs to be maintained regardless of the season. In winter, a separate humidification system is required to adjust the indoor humidity due to the dry outside air. However, since the conventional humidification system injects water or steam directly into the air, various problems, such as water pollution, occur. Therefore, this study proposed a new humidification method called the hollow-fiber membrane humidification system to increase indoor humidity, and the effect was experimentally evaluated. When 150 CMH (air volume of ventilation level) was supplied, the absolute humidity increased by about 4.14g/kg compared to the initial condition, and the relative humidity of the indoor supply air increased to about 64%.

1 Introduction

1.1 Research background

Recently, indoor humidity has been discussed as a critical issue in the building industry. If indoor humidity is higher or lower than the appropriate level, viruses, fungi, and bacteria can actively spread and cause harm to the human body [1]. However, the Passive House Annual Indoor Temperature and Humidity Report indicate that indoor humidity in buildings is below average in winter and relatively high in summer [2]. In addition, following a satisfaction survey of residents on indoor humidity, over 85% of respondents reported that indoor air is dry in winter [3].

Several humidification systems are available to maintain indoor moisture in buildings: ultrasonic [4], steam [5], etc. Ultrasonic humidification is the most common method used and can be produced in various sizes, so it is widely applied to humidifiers used individually in the room [4]. The steam system has the effect of sterilizing the air by steam and has the benefit of high efficiency. However, much energy is used to generate steam, a source of heat for humidification [5]. In all these humidifying techniques, latent heat and heat exchange occurs through direct contact between water and air. Contaminants in the water can, therefore, migrate into indoor air. In addition, the techniques used to prevent cross-contamination (i.e., steam, heating) require more energy for sterilization.

Previous studies of air-fluid membranes are as follows. Bergero and Chiari [6] have conducted experimental and theoretical studies on air's humidification/dehumidification processes in cross-flow hollow fiber contactors. Furthermore, a numerical model for predicting heat and mass transfer through the membrane was developed and compared with the experimental results. Zhang et al. [7,8] The effects of the hollow fiber membrane humidification module parameters were analyzed and tested experimentally and numerically. Additionally, a two-dimensional transient model combining Knudsen flow and the overall membrane pore diffusion mechanism was proposed and tested [9].

In summary, previous studies have concentrated on numerical analysis of heat and mass transfer or improving the performance of membrane materials for moistening air in membranes. However, the flow paths for hollow fiber membrane capacity design, operational parameters, and the range of construction applications have yet to be studied. In addition, the experimental analysis of the air-water method available in buildings requires further investigation. Therefore, in this study, a hollow fiber membrane humidification system, a new humidification method to increase indoor humidity in winter, was proposed, and the system's performance was reviewed by conducting parametric studies on operating variables.

The hollow fiber membrane humidification system proposed in this study simulated a small humidification system by installing 10 hollow fiber membrane modules. The hollow fiber membrane humidification module used in this study has a columnar structure, supplies water to the feed side and dry air to the permeate side, and exchanges heat and materials across the hollow fiber membrane. At this time, moisture in water having a relatively high vapor pressure is desorbed across the

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hollow fiber membrane. Then, due to the partial vapor pressure difference between water and air, it moves into the air through absorption and diffusion through the hollow fiber membrane. Finally, the air passing through the hollow fiber membrane humidification module is humidified and then supplied to the room.

As the hollow fiber membrane humidification system proposed in this study does not directly exchange water and air, there is no contamination problem during humidification. In addition, since the hollow fiber membrane, once wet, retains moisture for a certain period, there is an advantage in that the indoor humidity can be maintained for a specific time without circulating water.

2 Experiment Overview

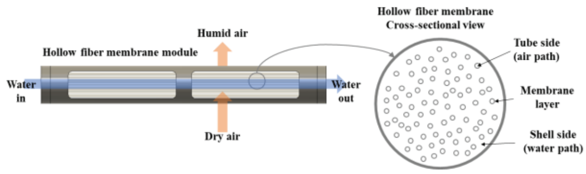
2.1 Experiments setup

In this study, a humidification module consisting of a porous hollow fiber membrane in which hydrophilic and polymeric materials are mixed was used. A small humidification system was created by configuring 10 modules. The dimensions of the hollow fiber membrane humidification system are 340mm (W) × 500mm (L) × 330mm (H). Each hollow fiber membrane module used had an inner diameter (ID) of 0.85 mm and an outer diameter (OD) of 1.05 mm, and the number of membrane strands was 3,800. The specifications for the membranes used are listed in Table 1.

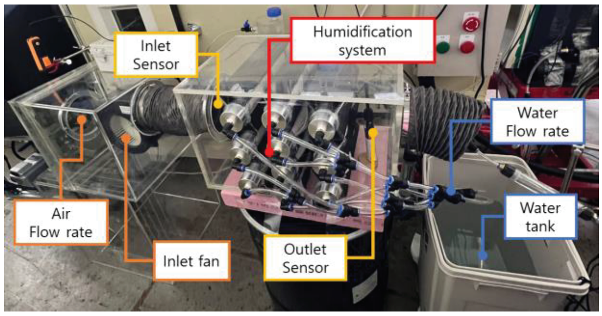
Fig.1 is an experimental configuration diagram of the hollow fiber membrane humidification system, which consists of a hollow fiber membrane humidifier, inlet/outlet temperature sensor, flow meter, air compressor, constant flow pump, and constant temperature and humidity room. The indoor air was supplied by creating indoor temperature and humidity conditions in winter using a constant temperature and humidity room. In the case of supplying water, the water temperature was set based on the water tank temperature using a heater and a cooler, and the water flow rate was controlled by adjusting the opening rate of the valve. Table 2 shows the specifications of the equipment used to measure operating variables.

Table 1. Humidification system specifications.

Design parameter	Details
Membrane type (material)	Dense membrane + hydrophilic coating
Membrane module size [mm]	340 (W)× 500 (L)× 330 (H)
Inner diameter (ID) [mm]	0.40 mm
Number of fibers [ea]	3,800 ea
Effective contact area [m^2]	1.43 m^2
Number of modules [ea]	10 ea



(a) Detailed view of the hollow fiber membrane module



(b) Experimental setup

Fig. 1. Hollw fiber membrane humidification system experimental setup

Table 2. Measuring device specifications.

Parameter	Type	Range	Accuracy
Air temperature and humidity	Negative Temperature Coefficient of Resistance (NTC)	-20 ~ 60 ℃ 0 ~100 %	± 0.5 ℃ ± 2.0 %
Air flow rate	Vane probe 100 mm	0.1-1.5 m/s	± 0.1 m/s
Water temperature	Thermocouple type K	-50 ~ 400 ℃	± 1.0 ℃
Water flow rate	LZT panel flowmeter	5 ~ 50 L/min	± 4.0 %

2.2 Experiments cases

Five variables were measured to evaluate the humidification performance of the hollow fiber membrane humidification module: air inlet and outlet temperature, relative humidity, absolute humidity, air flow rate, and water temperature and flow rate. Air flow rate, water temperature, and water flow rate were selected as operating variables for each experimental case. In addition, experiments were conducted on the performance of humidification as a function of water temperature (Case 1) and the ratio of water to air flow rate (Case 2). When evaluating the humidification performance (case 1) according to the water temperature, the air temperature and humidity, air flow rate, and water flow rate were kept constant, and the water temperature was varied in six stages in the range of 10 to 50 °C.

When evaluating the humidification performance (case 2) according to the ratio of water flow rate, the air temperature, humidity, and water temperature were kept the same, and the ratio of water to air flow rate was varied in 13 stages in the range of 0.0005 to 0.012. Based on each ratio of air-to-water flow rate, the airflow rate was set to the minimum and maximum of 50 m^3/h and 300 m^3/h, respectively, and the water flow rate was changed from a minimum of 1.8 L/min to a maximum of 12.0 L/min. Experimental conditions for operating variables are shown in Table 3. Furthermore, the conditions of the dependent variables for each experimental case are set out in Table 4. All experiments were replicated two to four times for reproducibility.

Table 3. Experiment conditions

Parameters	Case 1		Case 2	
	Min	Max	Min	Max
Inlet Air temperature (℃)	20 (±2.0)		20 (±2.0)	
Inlet Air relative humidity (%)	40 – 50 (±5.0)		40 – 50 (±5.0)	
Air flow rate (m^3/h)	150		50	300
Water flow rate (L/min)	12.5		1.8	12.0
Water temperature (℃)	10	50	20	

Table 4. Experimental cases

Case	$\dot{m}_{a.in}$ $[m^3/h]$	$\dot{m}_{w.in}$ $[L/min]$	$\varphi_{w/a}$ $[-]$	$T_{w.in}$ [°C]
Case 1-1	150.0	12.5	0.0005	10
Case 1-2	150.0	12.5	0.0005	15
Case 1-3	150.0	12.5	0.0005	20
Case 1-4	150.0	12.5	0.0005	30
Case 1-5	150.0	12.5	0.0005	40
Case 1-6	150.0	12.5	0.0005	50
Case 2-1	200	1.8	0.0005	20.0
Case 2-2	200	3.5	0.001	20.0
Case 2-3	300	11.5	0.002	20.0
Case 2-4	150	8.5	0.003	20.0
Case 2-5	150	12.0	0.0048	20.0
Case 2-6	100	8.5	0.005	20.0
Case 2-7	55	5.5	0.006	20.0
Case 2-8	100	11.5	0.007	20.0
Case 2-9	95	12.0	0.008	20.0
Case 2-10	85	12.0	0.0085	20.0
Case 2-11	80	11.5	0.009	20.0
Case 2-12	50	8.5	0.010	20.0
Case 2-13	50	10.0	0.012	20.0

2.3 Performance indices

In this study, the humidification performance of the system was evaluated by two indicators: the difference in absolute humidity and humidification efficiency [10]. The difference in absolute humidity is calculated as the humidity of the inlet and outlet air in the humidification system (Eq. (1)). It is an index that evaluates the amount of increase in quantitative moisture. Humidification efficiency is the difference in absolute humidity that occurs at the maximum difference in absolute humidity (Eq. (2)). Currently, since the water vapor pressure of water is the same as that of saturated air, the absolute humidity of water is equal to the saturated absolute humidity of air at the same temperature [11].

$$\Delta w_{hum} = w_{a.out} - w_{a.in} \tag{1}$$

$$\varepsilon_{hum} = \frac{Actual\ humidity\ variance}{Ideal\ humidity\ variance} = \frac{(w_{a.out} - w_{a.in})}{(w_{w.in} - w_{a.in})} \tag{2}$$

where,

Δw_{hum} = Difference in absolute humidity [g/kg]
ε_{hum} = Humidification efficiency [%]
$w_{a.out}$ = Absolute humidity of outlet air [g/kg]
$w_{a.in}$ = Absolute humidity of inlet air [g/kg]
$w_{w.in}$ = Absolute humidity of supply water [g/kg]

3 Results of Experiment

3.1 Uncertainty analysis

Uncertainty analysis of the measured parameters and performance indices data was done according to the ASHRAE standard [12]. Using the propagation of error (B_y) defined by Eq. (4) and the random error (S_y) defined by Eq. (5), the overall uncertainty (U_y) in the measurement data (Eq. (3)). The fixed error (b_{x_i}) for each variable, computed by multiplying the sensor accuracy and the measurement's standard deviation, were used to estimate the propagation of error (B_y). The standard deviation of the measured data ($S_{(N)}$) and the total number of datasets (N) were used to evaluate the random error (S_y).

Table 5. Overall uncertainty of parameters [%]

Measured parameters		Uncertainty [%]	
		Case 1	Case 2
Independent Parameter	$T_{a.in}$ [°C]	0.43	0.41
	$RH_{a.in}$ [%]	0.18	0.11
	$\dot{m}_{a.in}$ $[m^3/h]$	0.14	6.18
	$T_{a.out}$ [°C]	4.92	0.34
	$RH_{a.out}$ [%]	0.25	0.21
	$T_{w.in}$ [°C]	7.07	0.1
	$\dot{m}_{w.in}$ $[L/min]$	0.01	0.29
Dependent Parameter	Δw_{hum} $[g/kg]$	0.81	0.04
	ε_{hum} $[-]$	0.02	0.03

Table 5 displayed the measured variable's overall uncertainty (U_y) and performance indices. Relative humidity, a sensor-related measurement, was used to determine the absolute humidity uncertainty. It was determined that the highest level of uncertainty for all variables did not exceed 10%, and it was established that the measurement was conducted under stable experimental conditions.

$$U_y = \sqrt{B_y^2 + S_y^2} \tag{3}$$

$$B_y = \sqrt{\left\{\sum_{i=1}^{j} \left(\frac{\partial y}{\partial z_i} \cdot b_{x_i}\right)^2\right\}} \tag{4}$$

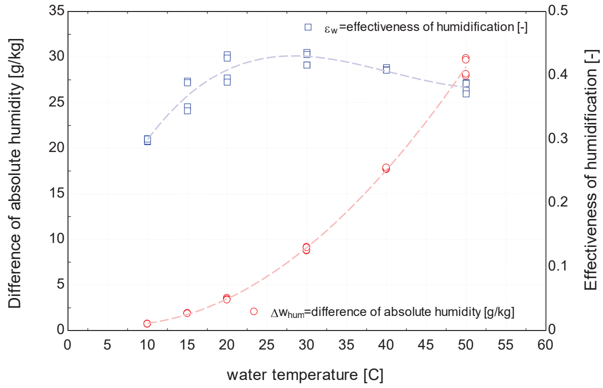
$$S_y = \frac{2 \cdot S_{(N)}}{\sqrt{N}} \tag{5}$$

3.2 Results of experiments

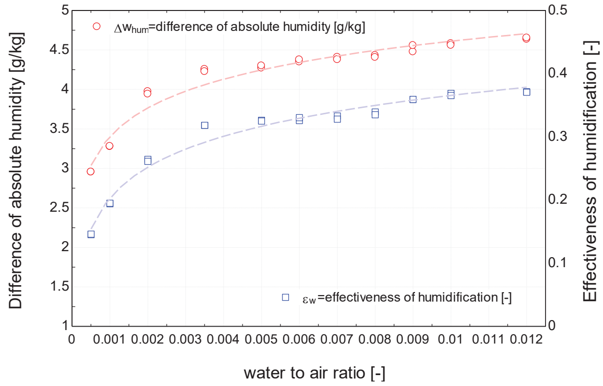
This study performed experiments on 6 conditions of case 1 and 13 conditions of case 2. Experimental conditions and results for each condition are listed in Table 6. The results in Table 6 mean the average values for repeated experiments. Fig. 2 shows the effect of the dependent variable. Fig. 2(a) shows the humidification performance according to the water temperature. Fig. 2(b) shows the humidification performance according to the air volume ratio of water to air.

As a result of the experiment in case 1, it was confirmed that the hollow fiber membrane humidification system rapidly increased the absolute humidity difference as the water temperature increased (absolute humidity difference ranged from 0.71 g/kg to 28.91 g/kg). This is because the water vapor pressure increases as the water temperature increases, so the difference in water vapor partial pressure between air and water increases the movement of moisture. On the other hand, the humidification efficiency did not change significantly according to the water temperature (humidification efficiency ranged from 0.3 to 0.4). This is because as the water temperature increases, the absolute humidity of the water increases, and the denominator of Eq. (2) increases. However, the actual moving amount of water (the numerator value of Eq. (2)) also increases accordingly, so the overall humidification efficiency changes insignificantly.

As a result of the experiment in case 2, the hollow fiber membrane humidification system showed that the difference in absolute humidity increased as the ratio of water to air flow rate increased, then converged to a certain level (absolute humidity difference ranged from 2.51 g/kg to 3.97 g/kg). Similarly, humidification efficiency showed a tendency analogous to the difference in absolute humidity (humidification efficiency showed a range of 0.2 to 0.4). This is because as the air volume ratio of water to air increases, the amount of water that can be delivered to the air increases, but since there is a limit to the humidity that air at 20 ℃ can contain, the absolute humidity difference and humidification efficiency increase and then converge.



(a) Humidification performance according to T_w [℃]



(b) Humidification performance according to $\varphi_{w/a}$ [−]

Fig.2. Effects of independent parameters

4 Conclusions

In this study, the performance of a hollow fiber membrane humidification system to increase indoor humidity in winter was experimentally reviewed, and a parametric study was conducted on the system. Two cases were classified according to the main operating variables: 1) humidification performance according to water temperature (T_w [℃]), 2) humidification performance according to the ratio of water to air flow rate ($\varphi_{w/a}$ [−]).

Case 1 divided the conditions into 6 stages based on the water temperature range of 10 ~ 50 ℃. Case 2 was divided into 13 stages in the range of 0.0005 to 0.012 according to the ratio of water to air flow rate. The effect of operating variables on the humidification performance of the hollow fiber membrane humidification module under each condition was analyzed through the experimental results. In Case 1, the difference in absolute humidity increased rapidly as the water temperature increased, but there was no significant difference in humidification efficiency. In Case 2, as the air volume ratio of water to air increased, the absolute humidity difference and humidification efficiency increased and then converged.

In this experiment, the humidification performance of the small hollow fiber membrane humidification system was experimentally verified. In future studies, we plan to present a humidification performance prediction model for operating variables based on more experimental data and perform model verification.

Table 6. Inlet and outlet air-condition according to test

Case.	*#.*	*Inlet air conditions (avg.)*				*Water conditions (avg.)*		*Outlet air conditions (avg.)*			***Results (avg.)***	
		$T_{a.in}$ [°C]	$RH_{a.in}$ [%]	$w_{a.in}$ $[kg/kg]$	$\dot{m}_{a.in}$ $[m^3/h]$	$T_{w.in}$ [°C]	$\dot{m}_{w.in}$ $[L/min]$	$T_{a.out}$ [°C]	$RH_{a.out}$ [%]	$w_{a.out}$ $[kg/kg]$	Δw_{hum} $[g/kg]$	ε_{hum} $[-]$
$Case$ 1	*1*	19.0	40.9	0.0056	149.7	**9.7**	12.5	13.4	65.6	0.0063	**0.71**	**0.3**
	2	18.8	43.3	0.0058	150.1	**15.4**	12.5	16.2	67.4	0.0077	**1.90**	**0.4**
	3	20.0	44.3	0.0064	150.0	**20.2**	12.5	19.9	68.3	0.0099	**3.47**	**0.4**
	4	19.1	46.2	0.0063	150.0	**30.1**	12.5	26.3	71.0	0.0153	**8.92**	**0.4**
	5	19.1	43.6	0.0060	150.1	**40.2**	12.5	33.6	71.7	0.0238	**17.80**	**0.4**
	6	20.4	44.6	0.0066	150.3	**50.2**	12.5	40.2	73.6	0.0355	**28.91**	**0.4**
Min.		**18.8**	**40.9**	**0.0056**	**150**	**10**	**12.5**	**13.4**	**65.6**	**0.0063**	**0.71**	**0.3**
Man.		**20.4**	**46.2**	**0.0066**	**150**	**50**	**12.5**	**40.2**	**73.6**	**0.0355**	**28.91**	**0.4**
$Case$ 2	*1*	18.6	43.9	0.0058	**200.2**	19.8	**1.8**	18.4	60.8	0.0080	**2.15**	**0.2**
	2	18.3	44.0	0.0057	**200.3**	19.8	**3.5**	18.0	64.6	0.0083	**2.55**	**0.3**
	3	20.5	42.1	0.0063	**299.8**	20.2	**11.5**	20.0	64.4	0.0094	**3.09**	**0.4**
	4	19.5	42.3	0.0059	**149.9**	19.8	**8.5**	19.4	67.6	0.0095	**3.54**	**0.4**
	5	20.8	43.4	0.0066	**149.8**	20.2	**12.0**	20.0	69.5	0.0102	**3.56**	**0.4**
	6	18.6	44.5	0.0059	**100.0**	19.8	**8.5**	18.7	70.6	0.0095	**3.60**	**0.4**
	7	20.6	40.3	0.0061	**55.3**	20.1	**5.5**	19.6	68.0	0.0097	**3.59**	**0.4**
	8	19.6	43.1	0.0061	**99.6**	19.7	**11.5**	19.3	69.6	0.0097	**3.64**	**0.4**
	9	20.2	41.2	0.0060	**95.3**	20.1	**12.0**	19.6	68.5	0.0097	**3.70**	**0.4**
	10	19.3	41.4	0.0057	**85.0**	19.8	**12.0**	19.2	68.1	0.0095	**3.73**	**0.4**
	11	19.6	41.5	0.0059	**80.3**	19.9	**11.5**	19.8	67.8	0.0098	**3.87**	**0.4**
	12	20.3	39.7	0.0059	**50.2**	20.0	**8.5**	20.5	65.3	0.0098	**3.94**	**0.4**
	13	20.1	41.1	0.0060	**50.1**	20.1	**10.0**	19.8	69.2	0.0099	**3.97**	**0.4**
Min.		**18.3**	**39.7**	**0.0057**	**50**	**20**	**1.8**	**18.0**	**60.8**	**0.0080**	**2.15**	**0.2**
Man.		**20.8**	**44.5**	**0.0066**	**300**	**20**	**12.0**	**20.5**	**70.6**	**0.0102**	**3.97**	**0.4**

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