

An Experimental Study on the Effect of Outdoor Temperature and Humidity Conditions on the Performance of a Heat Recovery Ventilator

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SUMMARY

The purpose of the present paper is to investigate the effect of outdoor weather conditions on the performance of a plate-type heat recovery ventilator. The performance should not be affected in a theoretical point of view. However, the performance varies in real applications, because of air leakage, motor heat generation, and etc. Experiments have been conducted to measure the sensible, latent, and enthalpy efficiencies by varying outdoor temperature and humidity conditions with the indoor conditions fixed at the standard heating or cooling conditions. The coefficient of energy has been introduced to quantify recovered energy in comparison with the electric power consumption.

Results indicate that the temperature exchange efficiency under winter conditions shows larger values than in summer conditions due to the heat generation by an internal fan. With the heat gain eliminated, the modified temperature efficiency remains almost constant regardless of outdoor temperature conditions. The enthalpy efficiency can exhibit very large values or negative values in case outdoor conditions are in the vicinity of the indoor enthalpy line. The direction of heat flow, in such a case, can be opposite to that of moisture flow between two air streams. Discussions are included about various interesting features of the psychrometric processes occurring in a heat recovery ventilator for various outdoor temperature and humidity conditions.

INTRODUCTION

Heat recovery ventilators are basically air-to-air heat exchangers to retrieve energy from building exhaust air. They are used to provide fresh ventilation air while saving heating and cooling energy. Heat recovery ventilators are expected to install commonly in apartment houses as well as in office buildings in Korea. The Act of Indoor Air Quality for Public Buildings [1] has been legislated and the Standards for Building Facilities [2] have been amended recently so as to include proper ventilation systems in public buildings and residential buildings.

The attestations for HRV's have been conducted by the Korea Energy Management Corporation [3] and the Korea Association of Air-conditioning Refrigerating and Sanitary Engineers [4]. However, the test conditions were different from each other and there were resolution problems in reporting test results depending on the temperature and humidity conditions and their uncertainties. A research has been conducted to provide theoretical backgrounds for the revision of the test protocol.

Theoretically speaking, heat recovery efficiency should be unchanged regardless of the indoor and outdoor temperature conditions. There are previous investigations that showed the dependence on the test conditions. Allan et al.[5] performed uncertainty analysis for an air-to-air heat exchanger installed in a commercial building and reported the efficiency can vary depending on outdoor weather conditions. Yoo et al.[6] compared the efficiencies of various paper plate-type heat exchangers for given outdoor conditions. Yee et al.[7] compared KS and JIS attestation standards and conducted sensitivity analysis. They raised a sensitivity issue related to the standard test conditions.

It is the objective of the present paper to investigate the effect of outdoor temperature and humidity conditions and their uncertainties on the performance results and their uncertainties so as to provide background information for revising the test protocol and to understand psychrometric processes occurring inside the heat recovery ventilator further.

METHODS

Experimental Apparatus

The heat recovery ventilator used in the present study is a ceiling-mount permeable fixed-plate heat exchanger. The HRV is one of typical kinds sold for apartment houses in the market. It has an average performance in terms of efficiency, capacity, and noise level. The measured values of the airflow rate and the electric consumption are 307CMH and 205W, respectively.

Experiments are conducted in Korea Test Laboratory. The test facility consists of two constant temperature chambers. The capacity of the calorimeter is 80MW, and the temperature range is $-50^{\circ}\text{C}\sim 100^{\circ}\text{C}$. The HRV is installed between two chambers as shown in Figure 1. Temperature measuring points are located three diameters away from the duct inlet. The accuracy in measuring temperature is within $\pm 0.1^{\circ}\text{C}$. Flow rates are measured beforehand according to the test method by KS A 0612 [8]. Return airflow rate is adjusted to match the supply airflow rate within $\pm 5\%$. The internal leakage rate is measured by a tracer gas method. A non-disperse infra-red detector is used to measure carbon dioxide concentration in each duct. The measurement range of the detector is 0~1000PPM, and the uncertainty is considered to be within $\pm 2\%$.

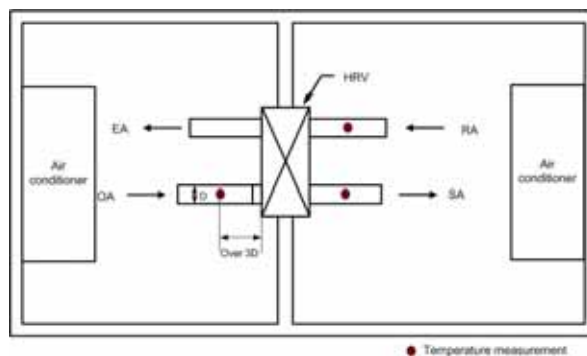


Figure 1. Schematic drawing of the test facility for heat recovery ventilators.

Experimental Conditions and Procedure

Table 1 shows the standard indoor and outdoor conditions by KARSE. The indoor condition is fixed for either heating or cooling condition, and various outdoor conditions are applied. The experimental conditions for indoor and outdoor are shown in Figure 2. The experimental number ‘C’ represents a cooling condition, and ‘H’ represents a heating condition. C0 and H0 are the standard test conditions by KARSE for cooling and heating conditions, respectively. C1 and C4 have the same humidity ratios with C0. C2 has the same temperature with C0, and C3 has the same enthalpy with C0. There is no difference between indoor and outdoor humidity ratios at C2, and therefore there is no moisture transfer. For heating conditions, H1 is the case when the relative humidity is the same with H0, and H2 and H3 are the cases when the enthalpy is the same with H0. Finally, H4 is a severe weather condition when condensation is expected to occur inside the heat exchanger module.

Table 1. Test conditions for HRV.

	Indoor condition		Outdoor condition	
	T _{dry} (°C)	T _{wet} (°C)	T _{dry} (°C)	T _{wet} (°C)
Cooling	24±0.3	17±0.2	35±0.3	24±0.2
Heating	22±0.3	13.9±0.2	2±0.3	0.44±0.2

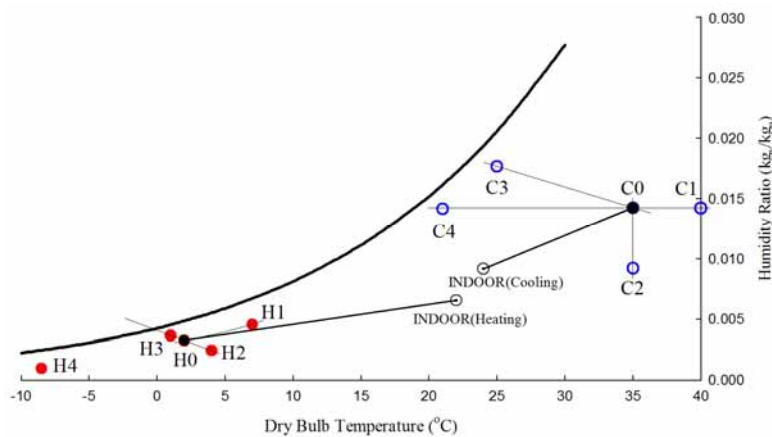


Figure 2. Test conditions shown on a psychrometric chart.

Each experiment is conducted after more than two hours when a steady state is reached for a given test condition. Dry-bulb and wet-bulb temperatures are measured for 30 minutes and averaged. The humidity ratio is obtained from the average dry-bulb and wet-bulb temperatures and the saturated vapor pressure at the temperature [9].

The temperature efficiency is defined as the ratio of the sensible heat recovered to the sensible energy difference between indoor and outdoor air.

$$\eta_T = \frac{T_{OA} - T_{SA}}{T_{OA} - T_{RA}} \times 100 \quad (1)$$

The humidity efficiency is defined in the same way for the latent heat. The enthalpy efficiency is the efficiency including both sensible and latent heat recovered by the heat exchanger.

$$\eta_h = \frac{h_{OA} - h_{SA}}{h_{OA} - h_{RA}} \times 100 \quad (2)$$

The effective enthalpy efficiency indicates the performance of energy transfer between supply and exhaust air excluding that by leakage. When the leakage ratio is zero, the effective efficiency is identical with the original enthalpy efficiency. As the leakage ratio increases, the supply air temperature approaches to the indoor air condition. When the leakage ratio is 100%, then the enthalpy efficiency becomes 100% as well. The effective enthalpy efficiency is always lower than the enthalpy efficiency. It is a function of leakage ratio as well as enthalpy efficiency, as is shown in Equation (3).

$$\eta_e = \frac{\eta_h - \eta_q}{100 - \eta_q} \times 100, \quad (3)$$

where η_q is the leakage ratio. Leakage ratio is the volumetric leakage rate divided by the supply airflow rate. It is measured beforehand by the tracer gas method according to the following equation. Carbon dioxide is injected into the return air duct and concentrations are measured in each duct.

$$\eta_q = \frac{C_{SA} - C_{OA}}{C_{RA} - C_{OA}} \times 100, \quad (4)$$

The coefficient of energy (COE) is defined as the recovered energy to the electric energy consumption. It indicates the cost benefits and usability of a heat recovery ventilator. The COE is not a unique property of a HRV but depends on test condition. As the indoor-outdoor enthalpy difference increases, the amount of recovered energy increases, while the denominator remains nearly constant. Therefore, the COE value changes from one test protocol to another.

$$COE = \frac{\rho \eta_e Q_e |h_{OA} - h_{RA}|}{W} \quad (5)$$

It should be noted that the airflow rate in the equation is the effective airflow rate, which is the supply airflow rate subtracted by the leakage airflow rate.

Uncertainty Analysis

Uncertainty analysis shows the effect of individual measured quantity on the efficiency results. The measured quantities are indoor and outdoor dry-bulb and wet-bulb temperatures. The enthalpies are calculated from the measured quantities. The uncertainties in temperature efficiency, humidity efficiency, and enthalpy efficiency are analyzed according to the root-mean-square method as followings.

$$\frac{\Delta Y}{Y} = \sqrt{\sum_{i=1}^n \left(\frac{\partial Y}{\partial x_i} \frac{x_i}{Y} \frac{\Delta x_i}{x_i} \right)^2} \quad (6)$$

RESULTS AND DISCUSSION

Table 2 shows the experimental results [10]. Various efficiencies and COE are shown with uncertainties associated. The humidity efficiency for C2 is not shown in the table, since there is no difference between indoor and outdoor humidity levels. Figure 3 shows the temperature and humidity efficiency results with uncertainty ranges. The horizontal axis shows the outdoor-indoor temperature difference, which is negative for heating conditions and positive for cooling conditions. As can be expected the error bar is large when the indoor-outdoor temperature difference is small. For most cases, temperature efficiency is in the range of 50~70%, whereas humidity efficiency is between 20~40%. It can be noticed the uncertainty in humidity efficiency is greater than that in temperature efficiency. This is due to the fact that the uncertainties in measuring humidity ratios are larger than those in measuring temperatures.

Table 2. Experimental results on various efficiencies and COE .

Experimental No	Temperature efficiency (%±%P)	Humidity efficiency (%±%P)	Enthalpy efficiency (%±%P)	Effective enthalpy efficiency (%±%P)	Coefficient of Energy (COE)
C0	58.75±1.09	20.49±3.95	38.72±1.86	32.66±2.05	3.47±0.23%
C1	61.35±0.78	19.17±3.98	42.53±1.57	36.85±1.73	4.70±0.24%
C2	57.68±1.13	-	61.68±3.56	57.89±3.91	2.81±0.23%
C3	-51.71±21.47	27.84±2.24	24.72±2.10	17.28±2.30	1.75±0.24%
C4	97.61±4.59	25.02±3.65	0.53±5.17	-9.31±5.68	-0.38±0.23%
H0	69.46±0.63	29.27±3.49	57.43±0.98	53.22±1.08	7.02±0.19%
H1	71.69±0.84	30.34±6.65	61.86±1.50	58.09±1.65	5.33±0.19%
H2	69.93±0.70	26.19±2.86	54.03±0.97	49.48±1.06	6.47±0.18%
H3	69.27±0.60	31.32±4.08	59.48±1.00	55.47±1.10	7.27±0.19%
H4	67.32±0.41	34.47±1.94	56.97±0.58	52.72±0.64	10.94±0.21%

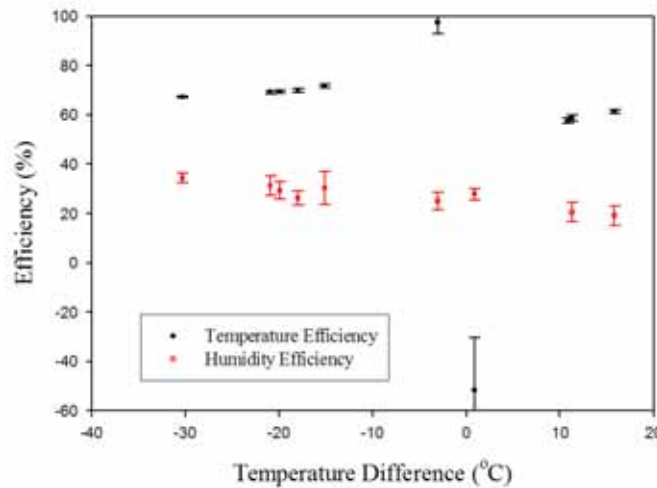


Figure 3. Temperature efficiency and humidity efficiency with respect to the indoor-outdoor temperature difference.

It is interesting to notice the temperature efficiency is negative for C3. This means the supply air has higher temperature than the incoming outdoor air for the heating condition. This is due to the temperature increase by a fan motor when the indoor-outdoor temperature difference is small.

As can be observed in Table 2, the effective enthalpy efficiency is lower than the enthalpy efficiency. Both of them are in the range of 30~60%. The COE is in the range of 2~10. As the power consumption of a fan motor is nearly constant, the COE can be considered to be proportional to the indoor-outdoor enthalpy difference.

Figure 4 shows processes on a psychrometric chart when outdoor air is passing through a HRV. The outdoor air at O reaches S' as it exchanges heat with return air. When temperature efficiency is greater than humidity efficiency, the slope of the line OS' is less steep than the line OR which represents the sensible heat ratio (SHR) of the space heating/cooling load.

The point moves from S' to S, as the heat generated by a motor is supplied to supply air. The temperature efficiency can be represented by the ratio of the length Rc to bc, consequently. In case the temperature rise is large enough so that the point b is beyond the point c, the temperature efficiency becomes negative, as for C3. Similarly, the humidity efficiency is the ratio of Od and Oc.

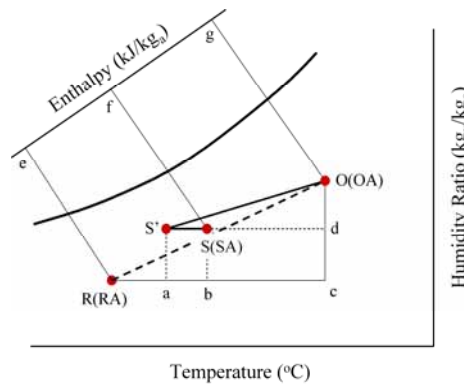


Figure 4. Process lines on a psychrometric chart inside a heat recovery ventilator.

The modified temperature efficiency is defined as the temperature efficiency with the internal heat gain removed, as shown in Equation (7). It is assumed that the heat gain is 50% of the power consumption of a fan motor. Yoo et al. [6] has estimated 40~50% in calculating internal heat gain.

$$\eta = \frac{T_{OA}(T_{SA} - \Delta T_m)}{T_{OA} - T_{RA}} = \frac{\overline{ac}}{\overline{Rc}} \quad (7)$$

As can be observed in Figure 5, the modified temperature efficiency is nearly constant, i.e. 64~68%, regardless of the outdoor conditions. It is interesting to notice the effective enthalpy efficiency of the case of C4. The outdoor temperature is lower but the humidity ratio is larger than the indoor condition. The direction of heat transfer is opposite to that of moisture transfer through heat exchange medium. As the enthalpy of C4 is quite close to that of indoor condition, the enthalpy efficiency can have any value with large uncertainty. In case, the enthalpy efficiency is lower than leakage ratio, the effective efficiency becomes negative.

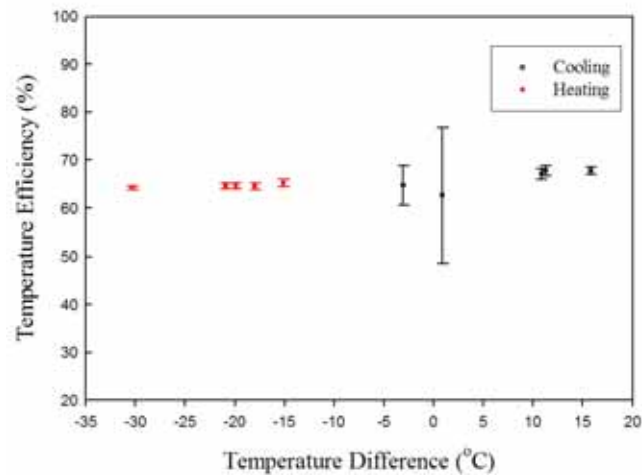


Figure 5. Temperature efficiency modified with the heat gain eliminated.

A psychrometric chart can be subdivided into several regions as shown in Figure 6. D is the region where most weather data fall on. A is the region where the effective enthalpy efficiency exceeds 100%, and B and C are the regions of negative efficiency. The enthalpy efficiency is positive in C but less than leakage ratio, so that the effective value is negative. The lines between these regions have specific slopes. The solid line is an enthalpy line.

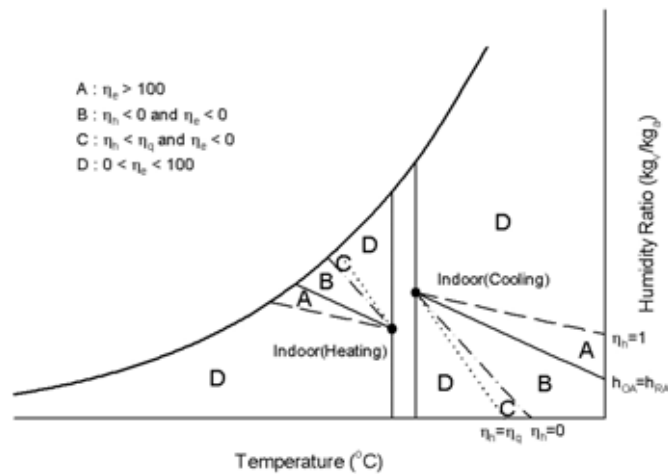


Figure 6. Psychrometric regions categorizing enthalpy efficiency.

CONCLUSIONS

Various outdoor temperature and humidity conditions are applied to a plate-type heat recovery ventilator to investigate the effect of weather conditions on various efficiencies and their uncertainties.

Firstly, the humidity efficiency is lower than the temperature efficiency for all cases regardless of heating or cooling weather conditions. The uncertainty of humidity efficiency is greater than that of temperature efficiency, since the uncertainty in measuring humidity is greater than that in measuring temperature.

One of the reasons that the efficiencies show different values depending on outdoor temperature and humidity is due to the heat gain by the internal heat generation of a fan

motor. That is the reason why the temperature efficiency is greater for a winter condition than a summer condition.

When the indoor-outdoor temperature difference is not large, it is possible that the temperature efficiency can show negative values. Results show that the modified temperature efficiency with the internal heat gain eliminated remains nearly constant and within the uncertainty range.

The enthalpy efficiency can be negative or over 100% when the indoor-outdoor enthalpy difference is small. The effective enthalpy efficiency can be negative in case the enthalpy efficiency is less than the leakage ratio.

NOMENCLATURE

C : Tracer gas concentration [ppm]
 C_p : Specific heat at constant P [kJ/kg·K]
 h : Enthalpy [kJ/kg(DA)]
 h_f : Saturated liquid enthalpy [kJ/kg]
 h_{fg} : Latent heat [kJ/kg]
 h_g : Saturated vapor enthalpy [kJ/kg]
 P : Pressure [Pa]
 \underline{Q} : Airflow rate [m³/h]
 T : Temperature [°C]
 W : Electric consumption [W]
 w : Absolute humidity [kg/kg(DA)]
 x_i : Measured value
 Y : Result

Greek

ρ : Supply air density [kg/m³]
 η : Efficiency

Subscripts

d : Dry air
e : Effective quantity
h : Total enthalpy
m : Motor
q : Air leakage
w : Moist air
OA : Outdoor air
RA : Return air
SA : Supply air

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