Possibility of preventing condensation in an energy recovery ventilator using a preheat coil powered by a photovoltaic system

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ABSTRACT

In this study, we proposed a preheater required for an energy recovery ventilator (ERV) to prevent condensation occurring in the winter. To determine the frost threshold temperature in the total heat exchanger, the temperature equation was derived from the psychrometric chart as a function of outdoor air (OA), exhaust air (EA) conditions and the total heat exchanger effectiveness. Additionally, the capacity of the preheater was estimated based on the frost threshold temperature. Moreover, the application of a photovoltaic system was proposed to supply the electric power required for preheater operation and energy savings. The photovoltaic module size was determined based on the peak preheater load. The electric energy consumption of the preheater and the photovoltaic system size were calculated for the Seoul region based on a residential building.

KEYWORDS

Energy recovery ventilator, Condensation, Frost, Preheater, Photovoltaic

INTRODUCTION

An energy recovery ventilator (ERV) is a component for exchanging heat and moisture between exhaust air (EA) streams and outdoor air (OA) streams because their temperature and humidity are different. This component improves indoor air quality and reduces energy consumption for cooling/heating load in ventilated spaces. For these reasons, ERVs are usually used in residential and commercial buildings. However, ERVs have condensation or frost issues during the winter season. If warm and humid exhaust air meets the cold surface of ERV or cold and dry OA obtains heat and moisture from the exhaust air, then condensation can occur in the ERV. When the surface temperature is lower than the freezing point, frosting will occur in exchangers (ASHRAE, 2016). Frost formation results in a reduction and eventual blockage of airflow through the exchanger, increases the electric power for the fans, decreases the heat transfer rate between exhaust air and OA, causes corrosion damage in exchangers and is harmful to an occupant's health (Jeon et al. 2013).

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Many methods have been suggested to solve the condensation and frosting issues in ERVs; however, several methods reduce the effectiveness of the ERV or cannot control the condensation completely (Rafati et al. 2014). Methods preheating the OA or reheating the exhaust air can solve the condensation problem in ERVs because these methods maintain the effectiveness of ERV and control the condensation (by preventing condensation). The preheat method is a general method that consumes less energy than the reheat method and has the same effect (Freund et al. (2003). However, additional energy consumption for preheating is not the only disadvantage and is un suitable for long-term use in cold regions (Rafati et al. 2014).

In this study, we confirmed which factors have an effect on the preheat coil operation and the capacity of the preheat coil. Additionally, the capacity of the preheat coil and the temperature of the frost threshold were calculated using mathematical analyses to prevent frosting based on the Korea weather data.

We proposed an ERV-PV system supplying electricity obtained from photovoltaic system to the preheat coil in the ERV to prevent condensation and frost using the preheat method.

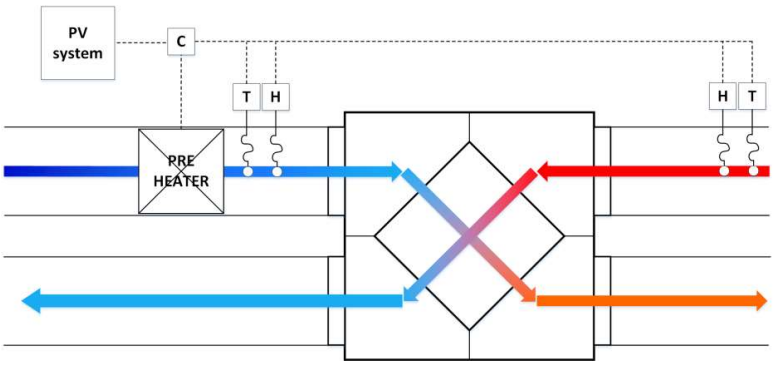
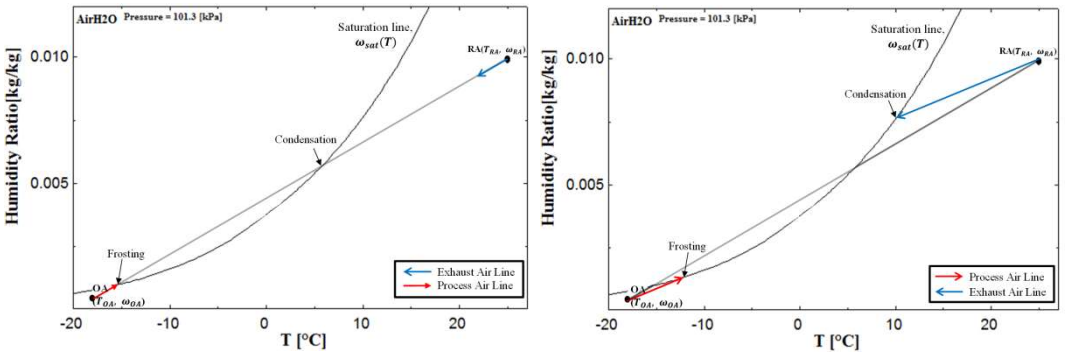


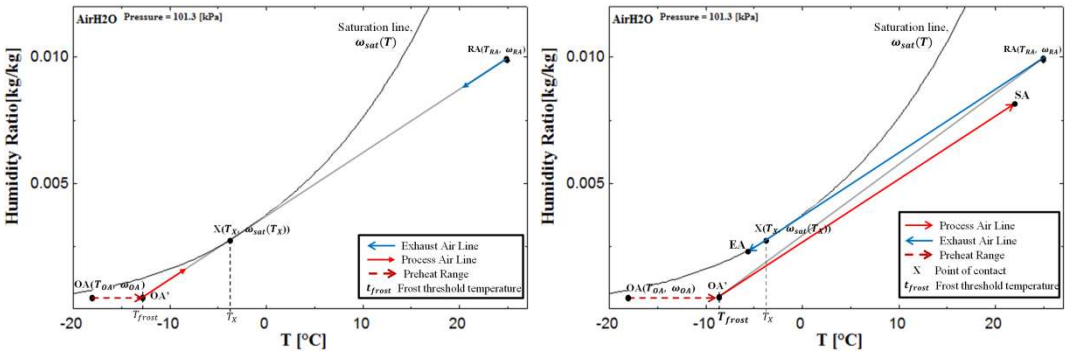
***Figure 1**. Schematic diagram of ERV-PV with preheater*

Condensation and preheating process in ERV

Condensation on the energy exchanger can occur in the ERV when total heat is exchanged between the OA and EA during the winter season, via cooling/ dehumidification of exhaust air and heating/humidification of OA. While exchanging the total heats, the states of OA and EA change such as the process air line and exhaust air line are shown on a psychrometric chart (Figure 2). If sensible effectiveness (ε_S) and latent effectiveness (ε_L) are the same, the state change rate of process air line and exhaust air line are the same as the slope of the connecting line with a state point of room air (RA) and OA. The majority of sensible effectiveness is higher than latent effectiveness in ERV, thus the exhaust and process air lines are shown in Figure 2-(b). If state points of OA and RA reach the saturation curve, condensation or frost can occur in the ERV. Therefore, preheating the OA is necessary to not meet the saturation curve with outdoor and process air line on a psychrometric chart, as shown in Figures 2-(c), (d). In this situation, the frost threshold temperature is the standard temperature to prevent the condensation and the temperature of preheated OA should be higher than the frost threshold temperature.



(a) Condensation process in ERV ($\varepsilon_S = \varepsilon_L$)*(b) Condensation process in ERV* ($\varepsilon_S > \varepsilon_L$)



(c) Condensation prevention in ERV ($\varepsilon_S = \varepsilon_L$) *(d) Condensation prevention in ERV* ($\varepsilon_S > \varepsilon_L$))

Figure 2. *Determination of frost threshold temperature in ERV*

The calculation process of the frost threshold temperature is as follows:

(1) The saturation curve can be determined as a linear regression based on temperature and absolute humidity (Eq. 1).

(2) Find the tangent point X ($T_X, \omega_{sat}(T_X)$) and tangent line from a given point RA (T_{RA}, ω_{RA}) to the one unknown point on a saturation curve (Eq. 2).

(3) Preheat the OA (T_{OA}, ω_{OA}) until OA′ ($T_{OA} + \Delta T, \omega_{OA}$)) to the exhaust air line and the saturation curves are tangent to each other.

As shown in Figure 2-(d), the exhaust air line is a standard way of determining the frost threshold temperature because the exhaust air line prevents condensation better than the process air line. The equation for sensible and latent effectiveness is shown in Equations 3 and 4, and the slope of the exhaust air line (m) is shown in Equation 5.

(4) If sensible effectiveness is higher than latent effectiveness, then multiply m by the effectiveness ratio ($\varepsilon_S/\varepsilon_L$) and the result is the slope of OA′and RA (m′) (Eq. 5).

(5) The frost threshold temperature is calculated from the slope of the exhaust air line being equal to the slope of tangent line (Eq. 7). Therefore, frost threshold temperature can be expressed as Equation 8.

The capacity of the preheat coil is calculated using the frost threshold temperature and mass flow rate (Eq. 9).

$$\omega_{sat}(T) = a_0 + a_1 T_1 + a_2 T_2 + a_3 T_3 + a_4 T_4 + a_5 T_5 + a_6 T_6 \quad (1)$$

Table 1. *Coefficient of* $\omega_{sat}(T)$

a_0	a_1	a_2	a_3	a_4	a_5	a_6
3.73E-3	2.88E-4	8.48E-6	1.31E-7	3.96E-9	6.37E-11	-1.56E-12

$$\omega_{RA} = \omega'_{sat}(T_X)\times(T_{RA} - T_X) + \omega_{sat}(T_X) \quad (2)$$

$$\varepsilon_S = \frac{T_{frost}-T_{SA}}{T_{frost}-T_{RA}} = \frac{T_{EA}-T_{RA}}{T_{frost}-T_{RA}} \quad (3)$$

$$\varepsilon_L = \frac{\omega_{OA}-\omega_{SA}}{\omega_{OA}-\omega_{RA}} = \frac{\omega_{EA}-\omega_{RA}}{\omega_{OA}-\omega_{RA}} \quad (4)$$

$$\mathrm{m} = \frac{\omega_{EA}-\omega_{RA}}{T_{EA}-T_{RA}} \quad (5)$$

$$\mathrm{m}' = \mathrm{m}\times\frac{\varepsilon_S}{\varepsilon_L} = \frac{\omega_{OA}-\omega_{RA}}{T_{frost}-T_{RA}} \quad (6)$$

$$\mathrm{m} = \frac{\omega_{OA}-\omega_{RA}}{T_{frost}-T_{RA}}\times\frac{\varepsilon_L}{\varepsilon_S} = \omega'_{sat}(T_X) \quad (7)$$

$$T_{frost} = (\omega_{OA} - \omega_{RA})\times\frac{\varepsilon_L}{\varepsilon_S}\times\frac{1}{\omega'_{sat}(T_X)} + T_{RA} \quad (8)$$

$$Q = C_p\times\dot{m}\times\Delta\mathrm{T} \quad (9)$$

The frost threshold temperature varies according to the condition of OA, RA and effectiveness of the energy exchanger. The frost threshold temperature is shown in Figure 3-(a) when the supply air condition is fixed at 20℃, 50% relative humidity and an effectiveness of energy exchange of ε_S=83.3%, ε_L=77.3%. Figure 3-(b) shows a preheat coil capacity according to room area when the air change per hour is 0.5 and the ceiling height is 2.3 m.

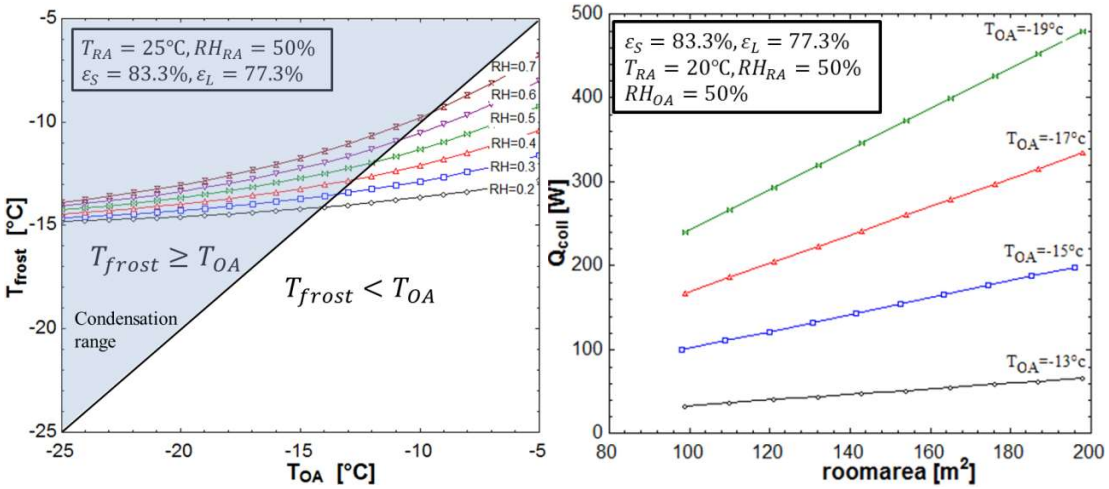


Figure 3. *Frost threshold temperature (left) and capacity of the preheat coil (right) according to OA conditions*

The maximum preheat coil capacity is 84.25 W and the maximum energy consumption is 573.2 Wh/day when the supply air conditions are 20℃, 50% relative humidity and an energy exchange of ε_S=83.3%, ε_L=77.3%, and the OA condition was based on the data from The Korean Solar Energy Society.

The operation condition of the preheat coil in ERV is determined by the frost threshold temperature, which is higher than the OA temperature (T_{OA}) and lower than the temperature of the tangent point (T_X). Figure 4 represents the control strategy algorithm of preheat coil in the ERV.

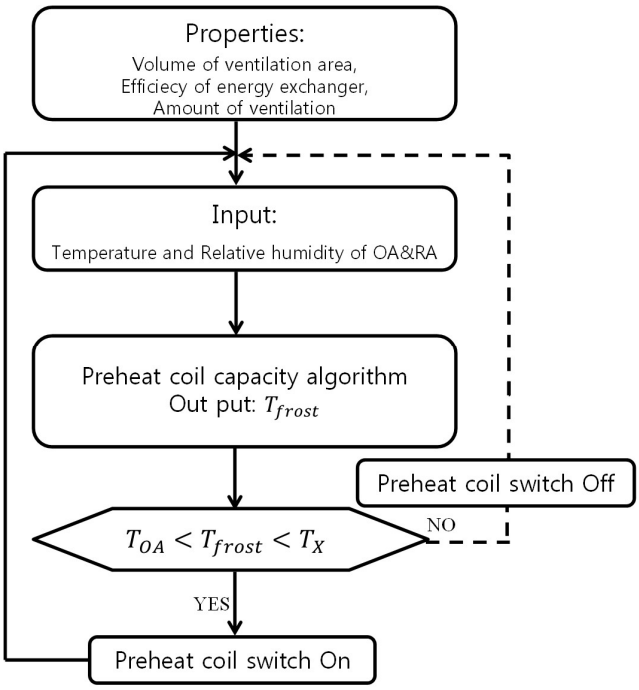


Figure 4. *Preheat coil control strategy of ERV*

PV system sizing

A photovoltaic panel is fixed facing south in the Northern Hemisphere and a surface tilted (β) at a latitude of $+15°$ was used to obtain maximum irradiation and cover the maximum preheat coil capacity. To determine the radiation on the tilted surfaces (I_T), an isotropic sky model consisting of the beam contribution ($I_b R_b$), diffuse on a horizontal surface (I_d), and solar radiation diffusely reflected from the ground ($I\rho_g$) was used (Eq. 10).

$$I_T = I_b R_b + I_d \frac{(1+cos\beta)}{2} + I\rho_g \frac{(1-cos\beta)}{2} \quad (10)$$

The calculation process of the PV array is as follows:

(1) Choose the system voltage (V_{sys}) from the maximum preheat coil capacity and calculate the number of series in the PV array using Equation 11.

(2) Using insolation data, find the peak sun hours during the worst month of the winter season along with a Coulomb efficiency, derating factor, and rated current by the specification of PV to determine the charge transferred to inverter per string (Eq. 12).

(3) The integer value for the number of parallel strings of modules are calculated by dividing the total load (Eq. 13) by Ah to inverter (Eq. 12) (Eq. 14).

$$\text{Modules in series} = \frac{V_{Sys}}{Nominal\ module\ voltage} \quad (11)$$

$$\text{Ah to inverter} = I_R \times \text{Peak sun hours} \times \text{Coulomb efficiency} \times \text{De-rating factor [Ah/day-string]} \quad (12)$$

$$Total\ load = \frac{\text{AC load [Wh/day]}}{Inverter\ efficiency \times V_{Sys}}\ \text{[Ah/day @ } V_{Sys}\text{]} \quad (13)$$

$$String\ in\ parallel = \frac{\text{Total load [Ah/day]}}{Ah\ to\ inverter} \quad (14)$$

In Seoul, the preheat coil of the ERV needs 573.2 Wh/day of ac delivered from an 85% efficient inverter. For a 12 V system voltage, a 90% Coulomb efficiency, and 90% derating factor, the results of the radiation on tilted surfaces and the PV (Kyocera KC120: 120-W module, I_R=7.1 A, V_{Max}= 16.9V) module sizing for supplying the energy consumption of the ERV preheat coil in Seoul are 2526 W/㎡ and 592.7 Wh/day, respectively. Therefore, the output of PV (592.7 Wh/day) satisfies its goal of 573.2 Wh/day ac.

$$\text{Storage days (99\%)} \approx 24 - 4.73 \times \text{Peak sun hours} + 0.3 \times (\text{Peak sun hours})^2 \quad (15)$$

$$\text{Nominal (C/20, 25}\,^{\circ}C\text{) battery capacity} = \frac{\text{usable battery capacity}}{MDOD \times (T,DR)} \quad (16)$$

$$\text{Number of batteries in series} = \frac{V_{Sys}}{Nominal\ battery\ voltage} \quad (17)$$

$$\text{Number of strings of batteries in parallel} = \frac{\text{Total storage capacity}}{capacity\ of\ a\ single\ battery} \quad (18)$$

Equation 15 gives an estimate for days of battery storage needed to supply a load as a function of the peak sun hours per day during the design month. The usable battery capacity is calculated using Equation 16. The maximum depth of discharge (MDOD) and discharge rate factor (T, DR) are controlled by the type of batteries and temperature of the batteries location. The array of batteries was derived using Equations 16 and 17. If we use the Surette 12CS11PS (Lead acid type, V_{Max}=12 V, Ah @ C/20= 357), three parallel strings would give 983.49 Ah.
The PV system for the ERV diagram in Seoul, including some of the energy flows for January, is shown in Figure 5.

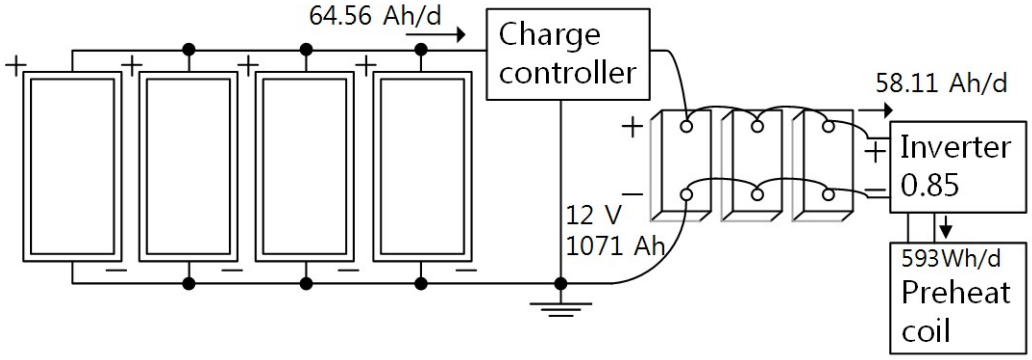


Figure 5. *PV Design for the ERV in Seoul, Korea*

Energy economics

Using the standard weather data of Seoul, the preheat coil used 996 Wh in January and 372 Wh in February. In terms of monetary value, the equivalent is the base rate (1,130 Won), respectively, and if applied to 1 apartment building with 90 households, it represents approximately 610,200 Won. If the ERV-PV system is installed, the annual energy savings equal approximately 1,800,000 Won for 1 apartment building according to the average system marginal price (SMP) for the year 2015.

CONCLUSION

In this study, we confirmed the process of condensation and frost in the ERV during the winter season, and to prevent it, we analyzed the optimum size for the preheat coil capacity and operating conditions. To determine the energy consumption of the preheat coil, we connected the PV system with ERV. The results from this study are as follows:

(1) When the sensible effectiveness (ε_S) is higher than the latent effectiveness (ε_L), the frost threshold temperature of ERV derived by exhaust air line (Fiugre 2-(d))

(2) The temperature of preheated OA should be higher than the frost threshold temperature, and the frost threshold is based on the OA, RA relative humidity, RA temperature, and ratio of ERV effectiveness (Eq. 8).

(3) For the operating conditions of the preheat coil, the frost threshold temperature should be higher than the temperature of OA and lower than the temperature of the contact point with the saturation curve and exhaust air line on a psychrometric chart ($T_{OA} < T_{frost} < T_X$).

(4) The weather data of The Korean Solar Energy Society was used to simulate the maximum capacity and energy consumption of the preheat coil in Seoul, which was 84.25 W, and 573.2 Wh/day when the room air conditions were $20\,°C$, 50% relative humidity, and an effectiveness of sensible and latent energy exchange of 83.3% and 77.3%, respectively.

(5) To prevent condensation in the ERV during the winter in Seoul, the cost of electricity for the preheat coil would be 610,200 Won for 1 apartment building with 90 households. The application of ERV-PV systems in this apartment building would be sufficient to preheat the coil, and the annual energy savings from PV in monetary terms would equal approximately 1,800,000 Won using the average system marginal price of the Korea Power Exchange standard.

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