

Preventing condensation and frosting in an energy recovery ventilator using a preheat coil

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ABSTRACT

One of the problems presented by energy recovery ventilators (ERV) is the condensation/frosting problem that occurs during winter time. In order to prevent this problem, preheating outdoor air is the most common method used nowadays. The aim of this research is to evaluate preheat coil capacities according to different indoor/outdoor inlet air conditions (temperatures and humidities) and sensible/latent effectiveness of ERV (ϵ_s , ϵ_L). Considering all these factors, formulas for calculating a frost threshold temperature (T_{Frost}) are suggested, T_{Frost} being the minimum inlet outdoor temperature at which condensation/frosting occurs under specific conditions. As a result, a control strategy for operating preheat coils for preventing condensation/frosting problems in ERVs is presented. For an ERV operating under outdoor inlet air conditions of -15°C and 70% indoor inlet air conditions of 22°C and 50% humidity, and sensible effectiveness is 80%, latent effectiveness is 70%, the capacity needed for the preheat coil is 227 W. In addition, preheat coil capacities were calculated for the operation of an ERV in a few cities of AIVC countries.

KEYWORDS

Energy recovery ventilator, Frosting, Condensation, Preheat coil

1 INTRODUCTION

Energy recovery ventilators (ERV) are mechanical ventilation devices that improve the indoor air quality (IAQ) and reduce cooling and heating load of an indoor area during ventilation in summer and winter times. The energy recovery is done by reusing the exhaust air's heat and moisture. However, when the ERV operates during the winter time, condensation can occur inside the total heat exchanger (THE) of the ERV while the sensible and latent heat is exchanged between the outdoor air and the exhaust air. If such condensation is exposed to freezing point, it may develop into frosting (ASHRAE, 2016). Both condensation and frosting phenomena can cause corrosion inside the ventilation system and/or increase microbial contaminants of the indoor air, what would threaten the health of building occupants (Jeon et al., 2013). In addition, condensation/frost may decrease the performance of the ERV, which may lead to the risk of cold air drafts as well as to the failure of the heat exchanger (Jang et al., 2008).

Various studies have been conducted to solve condensation and frosting problems in an ERV. Freund et al. (2011) compared the performance of various frosting control methods such as preheating outdoor air, reheating the exhaust air, controlling the wheel speed and bypassing the outdoor air using an enthalpy exchanger model. The results show that preheating outdoor air is the best method to prevent condensation/frosting in ERV. Nasr et al. (2013) explained the condensation and frosting process of the air-to-air heat/energy exchanger and compared the advantages and disadvantages of various methods that would be able to solve these problems. In the case of the HRV, condensation occurs when the temperature of the exhaust

air falls below the dew point temperature while exchanging sensible heat between the outdoor air and the exhaust air in the winter season.

Kim et al. (2016) confirmed the necessity of preventing condensation by calculating the time where condensation occur on the exhaust side of the HRV/ERV through a program for predicting the performance of the waste heat/energy recovery ventilation system.

2 CONDENSATION/FROSTING PROCESS IN ERV

During the winter, when the outdoor air and the exhaust air are exchanged through the total heat exchanger (THE) in ERVs, heat and moisture are transferred from the exhaust air side to the outdoor air side. Condensation or frosting occurs when the exhaust air temperature (Eq. (1)) drops below the dew point temperature of exhaust air during heat exchange (Eq. (2)). Condensation often occurs in most cases as the exhaust air is cooled and humidified.

$$T_{EA} = T_{RA} + \varepsilon_s(T_{OA} - T_{RA}) \quad (1)$$

$$T_{EA} < DPT_{EA} \quad (2)$$

Where T_{EA} is the outlet exhaust air temperature, T_{RA} is the inlet exhaust air temperature, T_{OA} is the outdoor air temperature, ε_s is the sensible effectiveness and DPT_{EA} is the dew point temperature of the outlet exhaust air.

3 PREVENTING CONDENSATION/FROSTING USING A PREHEAT COIL

Condensation or frosting is prevented by preheating the intake outdoor air at a temperature higher than a specific temperature (i.e., frost threshold temperature) and then performing heat exchange or more. In the following sections, present methods for predicting and preventing condensation/frosting using preheat coils at various effectiveness ratio in ERV.

3.1 Calculation of the frost threshold temperature of THE ($\varepsilon_s = \varepsilon_L$)

When the sensible and latent effectiveness are the same in the THE of the ERV, the state points of the exhaust process air and the inlet outdoor process air during the heat exchange, can be presented through a straight line (I.e., connect the OA&RA state points) in the temperature-humidity graph (T- ω graph).

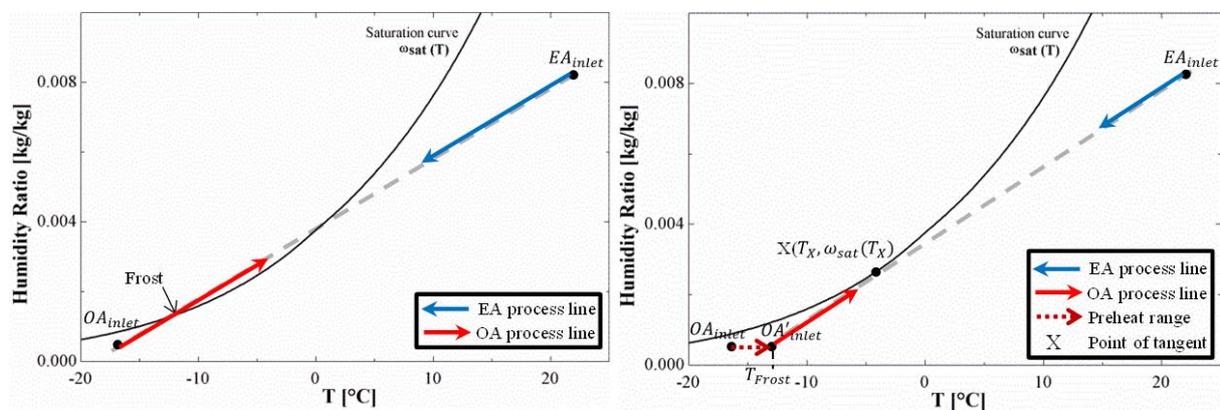


Figure 1.a) Condensation/frosting Process in THE ($\varepsilon_s = \varepsilon_L$) b) Condensation/frosting prevention in THE ($\varepsilon_s = \varepsilon_L$)

Condensation or frosting may occur when the state point reaches the saturation curve while outdoor air is getting heat and moisture from the exhaust air as shown by Fig. 1a (Kim et al.,

2016). On the other hand, in fig. 1b, it can be observed that condensation does not occur when the introduced outdoor air is preheated to a temperature that is higher than the frost threshold temperature (T_{Frost}). In this case, the straight line connecting the two state points (OA&RA) does not cross the saturation curve. The temperature at the point where a state point on the straight line in contact with the saturation curve from the state point of the indoor air is equal to the absolute humidity of the introduced outside air is the frost threshold temperature (Fig. 1b). Consequently, for preventing condensation/frosting in the total heat exchanger (THE), the introduced outdoor air should be preheated to higher than the frost threshold temperature.

$$m_{OA-RA} = \frac{(\omega_{RA} - \omega_{OA})}{(T_{RA} - T_{OA})} \quad (3)$$

$$\omega_{Sat} = a + b * T + c * T^2 + d * T^3 + e * T^4 \quad (4)$$

$$\omega'_{Sat}(T_X) = \frac{(\omega_{RA} - \omega_X)}{(T_{RA} - T_X)} \quad (5)$$

$$\omega'_{Sat}(T_X) = \frac{(\omega_{RA} - \omega_{OA})}{(T_{RA} - T_{frost})} \quad (6)$$

$$T_{frost} (\epsilon_S = \epsilon_L) = \frac{1}{\omega'_{Sat}(T_X)} (\omega_{OA} - \omega_{RA}) + T_{RA} \quad (7)$$

where m_{OA-RA} represents the slope of the straight line indicating the state point during the heat exchange between the outdoor air and the indoor air in the T- ω graph; ω_{RA} is the humidity of the exhaust air; ω_{OA} is the humidity of the outdoor air; ω_{sat} is the saturation curve (that depends on the absolute humidity, ω , and temperature, T); $\omega'_{sat}(T_X)$ is the slope of the straight line that connects the contact point X and the indoor air state point and $T_{Frost} (\epsilon_S = \epsilon_L)$ is the frost threshold temperature. The coefficients of Eq. (4) can be found in Table 1.

Table 1: Coefficients of saturation curve

a	b	c	d	e
3.73292975E-03	2.85006859E-04	8.47353550E-06	1.62517930E-07	3.49040153E-09

3.2 Calculation of the frost threshold temperature of THE ($\epsilon_S > \epsilon_L$)

Most of the ERV present higher values for sensible effectiveness compared to latent effectiveness in the total heat exchanger. In order to prevent condensation, the same principle of preheating the outdoor air to a temperature that is higher than the frost threshold temperature can be used when $\epsilon_S > \epsilon_L$. However, the method used for calculating the frost threshold temperature is different from the method presented for a THE in which sensible and latent effectiveness have the same values. The state points of outdoor air and indoor air during the total heat exchange are represented by straight lines (i.e., OA & EA process lines) in fig. 2a and 2b, having a slop obtained by multiplying the slope of the straight line connecting the two state points (OA&RA) by the heat exchange efficiency ratio (ϵ_L/ϵ_S) in the T- ω graph.

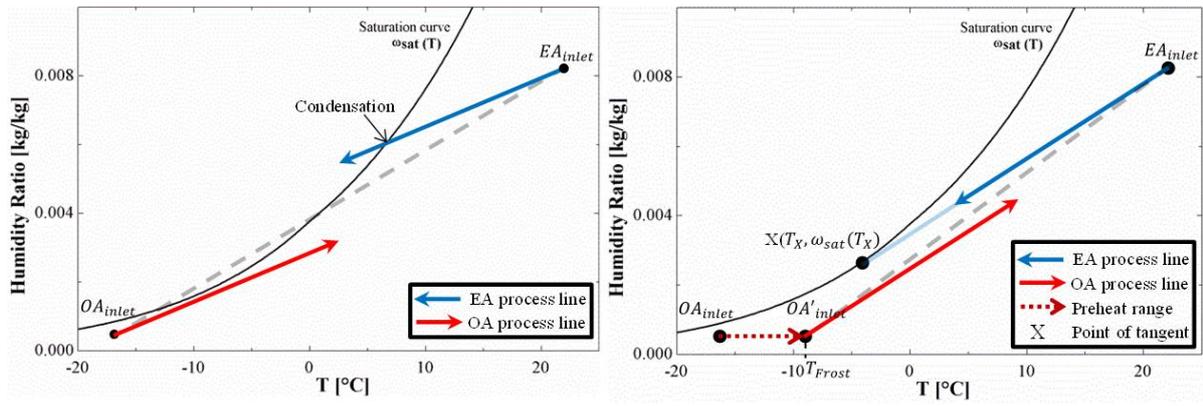


Figure 2. a) Condensation/frosting Process in THE ($\varepsilon_S > \varepsilon_L$) b) Condensation/frosting prevention in THE ($\varepsilon_S > \varepsilon_L$)

In Fig. 2, the two colorful lines are straight lines that show the changes in the state of the inlet outdoor air and exhaust air during the heat and mass exchange. Two important conclusions can be drawn from fig. 2: (1) The lines showing the state change of the exhaust and process air are parallel; (2) the EA process line is located above the OA process line and is close to the saturation curve.

If the EA process line does not cross the saturation curve, the OA process line will not cross either and, consequently, condensation and frost will not occur. Therefore, the EA process line in the T- ω graph will be the baseline for determining whether or not condensation in the THE of the ERV will occur.

For calculating the preheat coil capacity needed to prevent condensation in a THE that has different sensible and latent effectiveness the following procedure is suggested:

- (1) Draw a tangent line to the saturation curve starting from one state point (RA). At this time, the contact point between the saturation curve and the tangent line is called X (T_X , $\omega_{sat}(T_X)$).
- (2) Using Eq. (5), the equation of the tangent line between contact point X and indoor air point can be obtained.
- (3) In the T- ω graph, the slope of the EA process line is the slope of the straight line between state points OA and RA multiplied by the heat effectiveness ratio ($\varepsilon_L/\varepsilon_S$) (Eq. (8)).
- (4) If the slope of the EA process line is smaller than the slope of the tangent line, condensation will occur. Therefore, the frost threshold temperature is the outdoor temperature when the slope of the EA process line and the slope of the tangent line are the same.
- (5) Eq. (1), (8) and (9) can be summarized and an equation for the frost threshold temperature (Eq. (10)) is proposed.

$$\text{Slope of EA Process line} = \frac{\omega_{OA} - \omega_{RA}}{T_{OA} - T_{RA}} \times \frac{\frac{\omega_{EA} - \omega_{RA}}{T_{EA} - T_{RA}}}{\frac{\omega_{OA} - \omega_{RA}}{T_{OA} - T_{RA}}} \quad (8)$$

$$\varepsilon_L = \frac{\omega_{EA} - \omega_{RA}}{\omega_{OA} - \omega_{RA}} \quad (9)$$

$$T_{frost} (\varepsilon_S > \varepsilon_L) = (\omega_{OA} - \omega_{RA}) \times \frac{1}{\omega'_{sat}(T_X)} \times \frac{\varepsilon_L}{\varepsilon_S} + T_{RA} \quad (10)$$

$$Q = C_p \times \dot{m} \times (T_{Frost} - T_{OA}) \quad (11)$$

As can be seen from Eq. (10), the frost threshold temperature can be obtained by the indoor air temperature and humidity, the outdoor air temperature and absolute humidity, and the effectiveness ratio of heat exchange.

3.3 Control strategy for the preheating coil to prevent condensation/frosting

Through Eq. (10), it is possible to predict the state of the exhaust air and the occurrence of condensation or frosting in the total heat exchanger. Therefore, a control strategy for the operation of the preheating coil can be drawn based on both indoor and outdoor temperatures. It is important to mention that if the dry bulb temperature of EA process air is higher than the dew point temperature, the preheating coil will not operate because no condensation occurs. The following control strategy is presented for preventing condensation in a THE:

- (1) Enter the ventilation rate and the ventilation space size.
- (2) Obtain indoor & outdoor air condition data through temperature and humidity sensor.
- (3) The value of the sensible effectiveness and the latent effectiveness is calculated according to temperature and humidity data.
- (4) Determine the expected dry bulb temperature of the exhaust air through the sensible effectiveness equation (Eq. (1)). If the dry bulb temperature of the exhaust air is higher than the dew point temperature of the exhaust air, no condensation will occur and the preheat coil will not operate.
- (5) If the predicted dry bulb temperature of the exhaust air is less than or equal to the dew point temperature of the predicted exhaust air (which theoretically does not exist), then condensation may occur. Frost threshold temperature can be calculated by Eq. (7) or Eq. (10) depending on ϵ_S and ϵ_L .
- (6) Preheat coil capacity can be calculated by multiplying the specific heat of the air, the air flow rate, and the temperature difference between the outdoor air and the frost threshold temperature.

Process (2) to (6) can control the preheating coil operation according to indoor/outdoor temperature/humidity through the feedback process.

A diagram that presents the control strategy for the coil is shown on fig. 3.

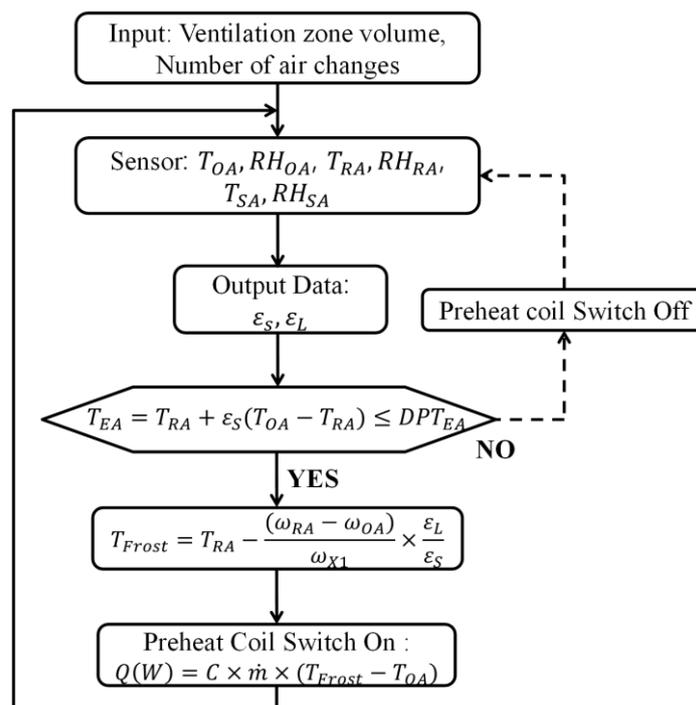


Figure 3. Preheat coil control strategy in ERV

4 SIMULATION RESULTS

4.1 Frost threshold temperature according to indoor air temperature and humidity

If the indoor air set point requires a lower temperature or requires a higher humidity, both temperature and humidity of the contact point $X(T_X, \omega_{\text{sat}}(T_X))$ will be higher. Therefore, the frost threshold temperature becomes higher, and condensation is likely to occur during the heat exchange. Conversely, when the indoor air set point requires a higher temperature or a lower humidity, the frost threshold temperature is lower and the probability to occur condensation during heat exchange diminishes (Fig. 4a).

Fig. 4b shows the frost threshold temperature according to indoor air conditions under 80% of sensible effectiveness and 70% of latent effectiveness.

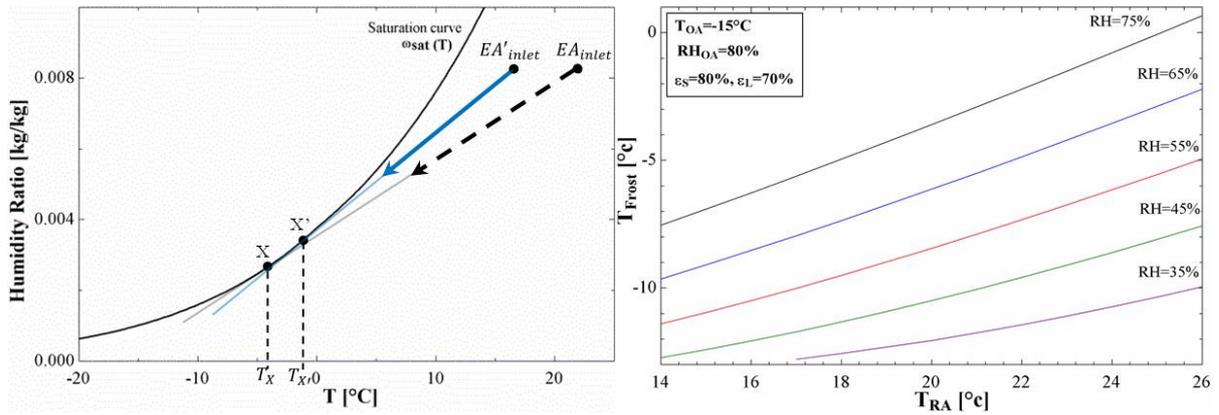


Figure 4. a) Change of contact point (X) of saturation curve according to indoor air set temperature
b) Frost threshold temperature for different outdoor air temperature and relative humidity

4.2 Frost threshold temperature according to outdoor air temperature and humidity

The Frost threshold temperature (Eq. (10)) calculation discussed in section 3 can be used to determine the frost threshold temperature according to the outdoor air temperature when indoor air condition is constant. Fig. 5 shows the frost threshold temperature according to various outdoor air conditions in the total heat exchanger. The values that were considered for heat exchanger effectiveness, indoor air temperature and relative humidity are $\epsilon_S = 80\%$, $\epsilon_L = 70\%$, 22°C and 50% , respectively.

When the relative humidity of the outdoor air is 40% , preheating is required when the dry bulb temperature of the outdoor air is below -12.7°C . If the outdoor air temperature is higher than -12.7°C , no condensation occurs during the heat exchange between the outdoor air and the exhaust air. Condensation occurs when temperatures inside the total heat exchanger reach -8.5°C or lower. For an outdoor temperature range of -30°C to 5°C and relative humidity range from 70 to 100% , the frost threshold temperature ranges from -11.2°C to 15°C as shown in Fig. 5. It can be seen that the higher the temperature and the relative humidity of the introduced outdoor air, the higher the frost threshold temperature.

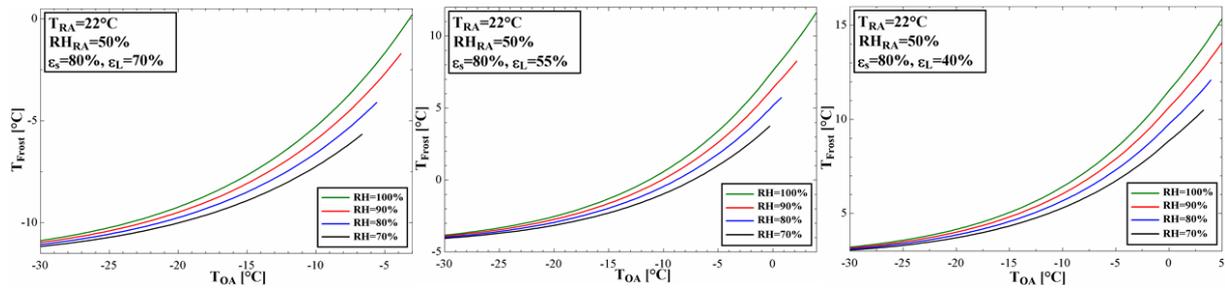


Figure 5. Frost threshold temperature according to outdoor air conditions and heat exchange effectiveness

As the heat exchange effectiveness ratio (ϵ_l/ϵ_s) becomes smaller, the frost threshold temperature becomes relatively higher (Eq. (10)) and the interval of the introduced outdoor air, which requires preheating, becomes shorter.

4.3 Required preheat coil capacity by region

Table 2 shows the calculated required capacity of the preheating coil in major cities of Belgium, Czech Republic, Denmark, France, Germany, Italy, Japan, Netherlands, New Zealand, Norway, Republic of Korea, Spain, Sweden, and United Kingdom. Room condition was set at 22°C and 50% humidity, ventilation zone volume was set at 195.5m³ and number of air changes was set at 0.5 times/hour. International Weather for Energy Calculations 2 (IWEC2) data was used for weather data.

Table 2. Frost threshold temperature and required capacity of preheating coils by region

Region	T _{Frost} (°C) (min/Max)	Preheat coil capacity (W)	Preheating time (Hour/Year)	Region	T _{Frost} (°C) (min/Max)	Preheat coil capacity (W)	Preheating time (Hour/Year)
London	-	-	-	Osaka	-	-	-
Birmingham	-3.1/1.6	118.6	29	Sapporo	-9/-1.8	168.8	328
Leeds	-0.5/1.0	108.5	7	Milano	-5.9/2.4	144.5	133
Stockholm	-9.1/2.4	316.2	876	Roma	-	-	-
Goteborg	-7.5/2.4	198.2	364	Torino	-0.6/2.4	122.2	18
Malmo	-8.9/2.4	335.4	364	Berlin	-6.8/2.4	192.9	333
Madrid	-3.3/2.4	122.2	37	Munich	-7.2/2.4	207.8	418
Barcelona	-	-	-	Frankfurt	-6.4/2.4	166.6	162
Valencia	-	-	-	Paris	-3.2/2.4	122.2	29
Seoul	-9.9/-2.1	211.2	177	Lyon	-6.5/2.4	125.2	108
Busan	-	-	-	Toulouse	-2.5/2.4	122.2	16
Incheon	-9.2/-1	176.4	145	Koebenhavn	-6.3/2.4	185.2	101
Oslo	-8.6/2.4	303.4	1082	Odense	-8.1/2.4	262.7	271
Bergen	-6.5/2.4	172.9	150	Aalborg	-5.3/2.4	166.8	232
Stavanger	-5.3/2.4	133.5	141	Praha	-7.8/1.5	232.9	322
Auckland	-	-	-	Brno	-8.9/2.4	377.3	646
Christchurch	-1.2/2.4	122.2	54	Ostrava	-9.1/2	359.7	450
Amsterdam	-5.9/2.4	137.3	169	Antwerpen	-4.9/2.1	120.5	57
Rotterdam	-6.5/2.4	170.5	149	Gent	-4.4/2.4	137.2	83
Eindhoven	-5.4/2.4	122.2	203	Charleroi	-5.4/1.4	115.6	198
Tokyo	-	-	-				

5 CONCLUSIONS

This study identifies possible condensation and frosting processes that may occur during winter in ERV and suggests preheating strategies that are able to prevent such problems. A

formula for calculating frost threshold temperature and the required preheat coil capacity to prevent condensation have been given.

Through this study, the following conclusions can be inferred:

- (1) Condensation occurs when the temperature of exhaust air (or introduced outdoor air) becomes lower than the dew point temperature during heat exchange. Therefore, it is possible to calculate the state of exhaust air in order to operate or not a preheating coil to prevent condensation.
- (2) In most ERVs, the sensible effectiveness is higher than the latent effectiveness. Therefore, condensation during heat exchange tends to occur on the exhaust side. When the outdoor air is preheated to a temperature higher than the frost threshold temperature to prevent condensation/frosting from occurring in the exhaust air, condensation does not occur in both the exhaust and the outdoor air.
- (3) When the sensible effectiveness and the latent effectiveness are the same ($\epsilon_S = \epsilon_L$), the frost threshold temperature is obtained from Eq. (7). If the sensible effectiveness is higher than the latent effectiveness ($\epsilon_S > \epsilon_L$), the frost threshold temperature is obtained from Eq. (10).
- (4) When indoor air and heat exchange effectiveness are constant, the frost threshold temperature increases in proportion to outdoor air and relative humidity. When the outdoor air temperature and the heat exchange effectiveness are constant, the frost threshold temperature increases in proportion to the indoor air temperature and the relative humidity.
- (5) IWEC2 weather data was used to calculate preheating coil capacity for several cities (Table 2). The capacity and preheating time of the preheating coil were the highest in Brno and Oslo. London, Barcelona, Valencia, Busan, Tokyo, Osaka and Roma are cities that do not need preheating coil.

6 ACKNOWLEDGEMENTS

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