Simulation of energy impact of an energy recovery ventilator in Northern housing

Jing Li, Radu Zmeureanu, and Hua Ge

Centre for Zero Building Energy Studies, Department of Building, Civil and Environmental Engineering, Gina Cody School of Engineering and Computer Science, Concordia University, Montreal, Qc, Canada

Abstract: The single core Energy Recovery Ventilator (ERV) used in this study is equipped with defrost control that recirculates the exhaust indoor air, while keeps the outdoor air intake damper closed. This defrost strategy has the disadvantage of reducing the outdoor air supplied to the house, which may affect the indoor air quality. First, this paper presents new correlation-based models of supply air temperature $T_2$ after the energy recovery core during normal and defrost operation modes based on laboratory experimental data. A pre-heating coil heats the supply air from $T_2$ to indoor air temperature. Second, a house in Montreal (4356 HDD) is simulated as a reference using TRNSYS program. Since the program cannot simulate the operation under defrost mode, the new models are connected in TRNSYS using equation boxes. The energy use of houses at three locations in northern Canada with HDD of 8798 (Inuvik), 8888 (Kuujjuaq) and 12208 (Resolute), are also simulated, without and with ERV unit. The seasonal energy used for heating the house and pre-heating the supply air is compared with results from Montreal. Compared to the case without heat recovery, the ERV unit leads to energy savings: 24% (Montreal), 26% (Inuvik), 27% (Kuujjuaq), and 27% (Resolute). Compared to the minimum standard requirements, the outdoor airflow rate due to defrost is reduced by 4.7% (223 hours) in Montreal, 19% (1043 hours) in Inuvik, 13% (701 hours) in Kuujjuaq, and 24% (1379 hours) in Resolute.

1. Introduction

Reducing energy consumption in buildings plays an important role in reducing CO$_2$ emissions since the building sector accounts for 40% of the global energy use [1]. New houses with higher airtightness and energy efficiency (R-2000-certified houses) have been increasingly constructed to reduce heat losses and their energy impacts during operation [2]. For relatively cold climates, to ensure air quality and thermal comfort as well as reduce energy use, finding the optimal mechanical ventilation solution is the concern in residential well-insulated buildings [3]. Energy use in ventilation systems without heat/energy recovery is significant in cold climates. To make a further reduction in energy use possible, it is essential to focus on high energy efficient ventilation and heat/energy recovery system [4].

The membrane energy exchanger (MEE) is recommended for cold climate applications because of its better performance on the frost-resistance and energy saving than other types of heat/energy exchangers applied to cold climates [5-7]. The formation of frost in the energy recovery ventilator (ERV) is the primary concern for the operation in cold climates. The frost occurs inside a membrane-based ERV when the outdoor air temperature is between $-8^\circ$C and $-12^\circ$C. The airflow rate of warm exhaust air entering the exchanger is reduced. As a result, the thermal efficiency of the unit diminishes, and the unit can be damaged if no measurements are taken to remove the frost [8-10].

Some publications [11-16] focused on the development of frost protection techniques and defrosting methods for the air-to-air heat/energy exchangers over the past 30 years in order to maintain high energy recovery effectiveness. Preheating the outdoor air, bypassing the outdoor airflow, reducing the supply airflow rate, and recirculating warm exhaust air have proved to be effective methods for the protection of exchangers [11,13]. The exhaust air recirculation was found to be the most appropriate for extremely cold climates [17]. When frost formation within the exchanger core reaches a critical level, the unit stops the supply of outside air, and the exhaust air is recirculated through the exchanger core to melt the accumulated frost.

HRV/ERV coupled with the recirculation defrost was widely investigated by laboratory-based experiments [8,14,18-20, 23]. However, to our knowledge, there are no publications on the analysis of HRV/ERV with the recirculation defrost, numerically or experimentally, for extremely cold climates.

The main objective of this paper is to evaluate the effect of recirculation defrost in ERV on: the total energy use of the house, the energy use for pre-heating outdoor air, the reliability of ERV in supplying the required outdoor air, and the effect on indoor humidity.
For this purpose, correlation-based ERV models are developed based on laboratory experimental data [8], and added to the energy model developed in TRNSYS for a Net-zero Energy house (NZEH) in Montreal [21]. This model is used for the analysis of single-core ERV using the manufacturer’s recirculation defrost schedule. The study includes also the assessment of this defrost method at three northern Canadian locations.

2. Methodology

2.1. NZEH house model

The NZEH model, developed in Type 56 in TRNSYS, is for a two-storey house with a ventilated attic and a basement. The house is divided into five zones including Zone A1/basement (41.23m²), ground floor Zone B1* (41.23m²), plus Zone B1+ (42.37m²), second floor Zone C1 (83.58m²), and unheated zones of a garage (42.4m²) and attic (83.6m²). The setpoint operative temperature of all heated zones is 22°C. Some features of the building envelope of the NZEH house model are presented in Table 1, while HVAC features in Table 2.

Table 1: Building envelope features of the NZEH house model

| Features                  | Technical information |
|---------------------------|-----------------------|
| Building heated floor area | 334 m²                |
| Occupancy                 | Two adults and three children |
| Above ground walls        | RSI-6.25 (m²·K/W)     |
| Basement walls            | RSI-2.47 (m²·K/W)     |
| Roof                      | RSI-10.42 (m²·K/W)    |
| Basement floor            | RSI-1.90 (m²·K/W)     |
| Windows                   | RSI-1.90 (m²·K/W)     |
| Natural Air Infiltration   | 0.061 ACH             |
| (airtightness)            | 1.22 ACH at 50 Pa     |

Note: Tables shows the effective thermal resistance of building envelope components

Table 2: Features of the HVAC system of NZEH house model [21]

| Equipment         | Technical information                        |
|-------------------|---------------------------------------------|
| Space Heating     | Hydronic radiant floor heating with an electric heaters and water storage tank (Type 534) |
| ERV               | Apparent sensible efficiency of 67% at 57 L/s and 0°C outdoor air temperature; 46% latent recovery efficiency at 57 L/s and 0°C outdoor air temperature |
| Defrost           | 7 min defrost and 25 min operation between -10 to -27°C, and 10 min defrost and 22 min at outdoor air temperature lower than -27°C |

2.2. Development and verification of ERV unit models during the normal and defrost operation

The supply air temperature \( T_2 \) that leaves the ERV varies with the outdoor air temperature \( T_{outdoor} \), and the defrost/frost operation regime. The supply air temperature \( T_3 \) that enters the house is kept constant at \( T_3 = T_{indoor} \), being controlled by the heating coil (HC), installed after the ERV (Figure 1). During the defrost by recirculation, the outlet of exhaust air and inlet of supply outdoor air are closed. The exhaust air from the house that enters the ERV unit is recirculated through the channels of the unit, and then enters the heating coil (HC) before being supplied to the house. The indoor air quality (IAQ) of the house is affected during the recirculation defrost because the stale exhausted air is reintroduced into the house; there is no outdoor air introduced into the house during the defrost operation.

![Figure 1: Schematic representation of air-to-air energy recovery system](https://example.com/figure1)

The estimation of electric power input to heating coil, which is used to increase the temperature of outdoor air stream from \( T_2 \) to \( T_3 \), is needed for the overall estimation of the energy demand of the house during the heating season. The duration of normal and defrost operation modes is set according to manufacturer’s specification (Figure 2).

![Figure 2: Schematic variation of supply air temperature \( T_2 \) of the single core ERV operation over time at \( T_1 = -20°C \) and \( T_3 = 22°C \).](https://example.com/figure2)

2.2.1. Development of correlation-based models of supply air temperature \( T_2 \) during normal operation

The frosting effect on the supply air temperature \( T_2 \) of energy recovery unit is not considered in the built-in energy recovery component in TRNSYS. Therefore, it is needed to develop different correlation-based models of supply air temperature during the normal operation and defrost operation, respectively.

A series of correlation-based models that predict the supply air temperature \( T_2 \) versus time \( t \) at different outdoor air temperatures \( T_i \) are developed (Table 3) based on Beattie’s experimental results [8]. Data points for \( T_i = -10°C \) and \( -15°C \) almost overlap. These models consider the effect of frost on the heat exchange process, if the frost occurs in the exhaust air channel. The correlation-based models of supply air temperature \( T_2 \) are written in the equation components of TRNSYS and integrated in the house model.
### Table 3: Correlation-based models of supply air temperature $T_2$ with respect to time $t$ for the first 30 minutes of normal operation

| $T_1$ [°C] | Correlation-based model | $R^2$ |
|------------|-------------------------|-------|
| -10        | $T_2=0.263 \cdot T_{1(0)} + 18.001$ | 0.99  |
| -15        | $T_2=0.397 \cdot T_{1(0)} + 20.044$ | 0.99  |
| -20        | $T_2=0.316 \cdot T_{1(0)} + 17.188$ | 0.99  |
| -25        | $T_2=0.319 \cdot T_{1(0)} + 15.869$ | 0.99  |
| -35        | $T_2=0.586 \cdot T_{1(0)} + 18.242$ | 0.99  |

Where $T_{1(0)}$ is the air temperature leaving the heat recovery unit at the beginning of the normal operation, which is equal to air temperature $T_2$ at the end of the defrost operation.

If the outdoor air temperature $T_1$ is different from the values listed in Table 3, a linear interpolation is used between the closest correlation models. For instance, if the outdoor air temperature is $T_1=-12.5$°C, the interpolation is made between the values of -10°C and -15°C at every time step $t$.

To avoid the interpolation, the outdoor air temperature $T_1$ needs to be included in the correlation-based model. **Equation 1** presents one single correlation-based model for the prediction of supply air temperature $T_2$, developed in terms of time $t$ and outdoor air temperature $T_1$ from measurements of reference [8].

$$T_2 = T_2(t=0) \cdot \left[ A \cdot t \cdot B \cdot (1 - e^{-C}) + D \right]$$  \hfill (1)

**Equation 1** corresponds to the specific ERV unit used in [8]. The coefficients of fitting curve are determined from measurements as follows: $A=0.006$, $B=0.328$, $C=0.097$, and $D=1.102$ (Figure 3) at -10°C, -15°C, -20°C and -25°C, and $A=0.004$, $B=0.559$, $C=0.18$ and $D=1.126$ at -35°C. The predicted supply air temperature $T_2$ (Equation 1) agrees well with the measurements of supply air temperature $T_2$ as the coefficient of determination $R^2$ has values between 0.96 and 0.99. Therefore, the supply air temperature $T_2$ can be calculated with **Equation 1** to avoid the interpolation using equations listed in Table 3.

![Figure 3: Measured and predicted supply air temperature $T_2$ at different outdoor air temperatures during normal operation](image)

### 2.2.2. Development of correlation-based models of supply air temperature $T_2$ during defrost operation

When defrost is required, the supply air inlet damper and exhaust air outlet damper are closed. The airflow is recirculated from the exhaust air inlet to the supply air outlet. The ERV (Type 667b) in TRNSYS does not take into account the melting effect in the ERV on the supply air temperature $T_2$. Therefore, correlation-based models of supply air temperature $T_2$ during the defrost operation are developed using available measurements from [8].

The following data points are available: (i) at the beginning of defrost, and (ii) at the end of defrost (Table 4).

| $T_1$ [°C] | Inlet $T_1$ [°C] | $T_2$ at the beginning of defrost operation [°C] | $T_2$ at the end of defrost operation [°C] |
|------------|------------------|-----------------------------------------------|---------------------------------------------|
| -10        | 21.7             | 14.1                                          | 18                                          |
| -15        | 21.7             | 13.8                                          | 18                                          |
| -20        | 21.7             | 12                                            | 18                                          |
| -25        | 21.7             | 10.45                                         | 18                                          |
| -35        | 21.7             | 8                                             | 18                                          |

The supply air temperature $T_2$ during the defrosting period is modelled with **Equation 2**, which represents the general pattern of variation as presented in [6] from detailed measurements at 5 s time intervals.

$$T_2 = A \cdot T_2(t=0) + (T_2(t=7\text{ or }10)-T_2(t=0)) \cdot (1-e^{-B \cdot t})$$  \hfill (2)

Where $T_2$ is the supply air temperature [°C], $T_2(t=0)$ is the supply air temperature [°C] at the beginning of defrost (Table 4); $A$ and $B$ are coefficients to be determined; $T_2(t=7\text{ or }10)$ is the supply air temperature at the end of defrost (Table 4); and $t$ is the time during defrost [minutes]. The correlation-based models of supply air temperature developed by **Equation 2** at different outdoor temperatures are listed in Table 5, and the predicted supply air temperature $T_2$ during the defrost operation is presented in Figure 4.

### Table 5: The correlation-based model of supply air temperature $T_2$ at different outdoor air temperature $T_1$ versus time $t$ during the defrost regime of 7 minutes and 10 minutes

| $T_1$ [°C] | Correlation-based model |
|------------|-------------------------|
| -10        | $T_2 = -10.0668 \cdot (18 + (18-13.8)/(1-e^{-0.5}))$ |
| -15        | $T_2 = -10.07 \cdot (13.8 + (18-13.8)/(1-e^{-0.5}))$ |
| -20        | $T_2 = -10.01 \cdot (18 + (18-13.8)/(1-e^{-0.5}))$ |
| -25        | $T_2 = -10.03 \cdot (18 + (18-13.8)/(1-e^{-0.5}))$ |
| -35        | $T_2 = -10.03 \cdot (18 + (18-13.8)/(1-e^{-0.5}))$ |

The supply air temperature $T_2$ is obtained by interpolating between the correlation-based models when the outdoor air temperature $T_1$ is not listed in Table 5.

To avoid the interpolation, the outdoor air temperature $T_1$ is included in the correlation-based model of supply air temperature $T_2$, developed in terms of time $t$ and outdoor temperature $T_1$ (Equations 3 and 4).

$$T_2 = AT_1 + T_2(t=0) + T_2(t=7\text{ or }10) \cdot T_2(t=0) \cdot (1-e^{-B \cdot t})$$  \hfill (3)

Where:

$$T_2(t=0) = 0.2497T_1 + 17.124$$  \hfill (4)
Equations 3 and 4 corresponds to the specific ERV unit used in [8]. The coefficients of fitting curve (Equation 3) are determined from measurements as follows: A = 0.0, and B = 0.533. The predicted supply air temperature $T_2$ (Figure 4) agrees well with the supply air temperature $T_2$ in Table 5 as the coefficient of determination $R^2$ has values of around 0.99.

Supply air temperature $T_2$ is calculated for the defrost operation with the correlation-based model (Equations 3 and 4) and coefficients A=0.0 and B=0.525, determined based on data from [23] at several outdoor air temperatures $T_1$. As shown in Figure 6, these predictions agree well with measurements with $R^2 = 0.97-0.99$.

2.2.3. Verification of correlation-based models for the normal and defrost operation

The verification of correlation-based models for the normal and defrost operations is made by comparing with measurements from reference [23] under the same initial supply air temperature when the outdoor air temperature $T_1 = -20^\circ$C (Figure 5).

The pattern of variation is quite similar, and the coefficient of determination is $R^2 = 0.78$ (Figure 5). The difference is greater during the first 10 min of normal operation, which may be attributed to the different physical characteristics of ERVs used by [8] and [23]. The correlation-based model with the coefficients (A=1.352E-05, B=0.265, C=0.28 and D=0.965), determined from data [23], has better prediction results with $R^2 = 0.95$ when compared to measurements from [23] (Figure 5).

Figure 4: Predicted supply air temperature from Table 5 and predicted supply air temperature $T_2$ by Equations 3 and 4 at different outdoor air temperatures during defrost operation

Figure 5: Comparison of predicted supply air temperature $T_2$ from the correlation-based models with the coefficients based on reference [8] and reference [23] during normal operation and experimental results from reference [23] at outdoor air temperature of $-20^\circ$C.

2.3. Development of correlation-based models of supply air humidity $w_2$ of normal and defrost operation

Moisture transfer between the outdoor air and exhaust air only occurs in the ERV unit. There is no change in the humidity ratio through the heating coil ($w_2 = w_5$) (Figure 1). The supply air humidity ratio $w_2$, leaving the ERV unit, decreases during the 22-25 min of normal operation, then increases during the 7-10 min defrost operation. After the defrost operation, the cycle of normal and defrost operations is repeated (Figure 7), where $w_1$ is outdoor humidity ratio and $w_3$ is inlet exhaust humidity ratio.

2.3.1. Development of correlation-based models of supply air humidity ratio $w_2$ of normal operation

The frosting effect on the supply air humidity $w_2$ of ERVs is not considered in the built-in energy recovery component in TRNSYS. Therefore, there is a need for developing different correlation-based models of supply
air humidity ratio $w_2$ during the normal operation and defrost operation, respectively. Beattie’s experimental results at -25 °C and -35 °C of outdoor temperature (Figure 8) [8] are used to obtain the results for the other specific outdoor temperature (-10°C, -15°C and -20°C) (Figure 8). The effect of frost on the heat exchange process is taken into consideration in these models. The correlation-based models of supply air humidity ratio $w_2$ written in the equation components of TRNSYS are integrated in the house model when the frost occurs in the indoor air exhaust channel, while the built-in energy recovery component (Type 667) in TRNSYS is utilized when the frosting does not occur.

Equation 5 predicts the supply air humidity $w_2$, in terms of time $t$ and outdoor air temperature $T_1$ from measurements of reference [8].

$$w_2 = w_2(t=0) \cdot [A \cdot T_1 + B \cdot (1 - e^{-ct}) + D]$$  \hspace{1cm} (5)

Where $w_2(t=0)$ is the supply air humidity leaving the ERV at the beginning of the normal operation, which is equal to supply air humidity $w_2$ at the end of the defrost operation: $A$, $B$, $C$ and $D$ are coefficients to be determined and $t$ is the time during the normal operation, from 0 to 25 minutes. Equation 5 corresponds to the specific ERV unit used in [8]. The coefficients of the fitting curve (Equation 5) are determined from measurements as follows: $A=0$, $B=0.448$, $C=0.738$, and $D=0.96$ at -10°C, -15°C and -20°C and $-25°C$ and $A=0.005$, $B=0.47$, $C=0.363$ and $D=1.16$ at -35°C. As shown in Figure 9, the predicted supply air humidity $w_2$ using Equation 5 are in good agreement with the measured values within the coefficient of determination $R^2$ between 0.96 and 0.99. Therefore, the supply air humidity $w_2$ can be calculated with Equation 5.

![Figure 8](image-url)  
**Figure 8:** Supply air humidity $w_2$ of ERV unit at $T_1$=-10°C, -15°C and -20°C versus time during normal operation and supply air humidity $w_2$ at $T_1$=-25°C, -35°C by experiment [8].

2.3.2. **Development of correlation-based models of supply air humidity $w_2$ of defrost operation**

The ERV (Type 667b) in TRNSYS does not consider the melting effect on the supply humidity $w_2$. Therefore, correlation-based models of supply air humidity $w_2$ during the defrost operation are developed based on available measurements from [8]. The following data points are available: (i) at the beginning of defrost, and (ii) at the end of defrost (Table 6). $T_1$ refers to the conditions at the end of normal operation, which influences the core temperature at the beginning of defrost by recirculation.

| $T_1$ °C | $w_2$ [g/kg] | $w_2$ at the beginning of defrost operation [g/kg] | $w_2$ at the end of defrost operation [g/kg] |
|---|---|---|---|
| -10 | 5.44 | 3.74 | 6.1 |
| -15 | 5.44 | 3.63 | 6.1 |
| -20 | 5.44 | 3.46 | 6.1 |
| -25 | 5.44 | 3.20 | 6.1 |
| -35 | 5.44 | 2.75 | 6.1 |

The supply air humidity ratio $w_2$ during the defrosting period is modelled with Equation 6, which represents the general pattern of variation as presented in [23] from detailed measurements at 5 s time intervals.

$$w_2 = A \cdot (w_2(t=0) + B \cdot (w_2(t=7 \text{ or } 10) \cdot (1 - e^{-ct}))$$  \hspace{1cm} (6)

Where $w_2(t=0)$ is the supply air humidity [g/kg] at the beginning of defrost (Table 6); $A$ and $B$ are coefficients to be determined; $w_2(t=7 \text{ or } 10)$ is the supply air humidity $w_2$ at the end of defrost (Table 6); and $t$ is the time during defrost [minutes]. The correlation-based models of supply air humidity $w_2$ developed by Equation 6 are listed in Table 7, and the predicted supply air humidity $w_2$ during the defrost operation is presented in Figure 12.
Table 7: Correlation-based model of supply air humidity \(w_2\) at different outdoor air temperatures \(T_1\) versus time \(t\) during the defrost regime of 7 minutes and 10 minutes

| \(T_1\) [°C] | Correlation-based model |
|--------------|-------------------------|
| -10          | \(w_2 = 0.012 (3.74 + (6.1 - 3.74) (1 - e^{0.05 t}))\) \(0 < t < 7\) minutes |
| -15          | \(w_2 = 0.0127 (3.63 + (6.1 - 3.63) (1 - e^{0.05 t}))\) \(0 < t < 7\) minutes |
| -20          | \(w_2 = 0.014 (3.46 + (6.1 - 3.46) (1 - e^{0.05 t}))\) \(0 < t < 7\) minutes |
| -25          | \(w_2 = 0.015 (2.75 + (6.1 - 2.75) (1 - e^{0.05 t}))\) \(0 < t < 7\) minutes |
| -35          | \(w_2 = 0.004 (8 + (6.1 - 8) (1 - e^{0.05 t}))\) \(0 < t < 10\) minutes |

For conditions that are different from those in Table 7, interpolation can be used. To avoid the interpolation, one single model for the prediction of supply air humidity \(w_2\) is developed with respect to time \(t\) and outdoor air humidity \(w_2\) (Equations 7 and 8).

\[
w_2 = AT_1 + w_2(t=0) + (w_2(t=10) - w_2(t=0)) (1 - e^{-Bt}) \tag{7}
\]

Where:

\[
w_2(t=0) = 0.0409 T_1 + 4.2133 \tag{8}
\]

Equations 7 and 8 corresponds to the specific ERV unit used in [8]. The coefficients of fitting curve (Equation 7) are determined from measurements as follows: \(A = 0.0\), and \(B = 0.539\). As shown in Figure 10, the predicted supply air humidity ratio \(w_2\) agrees well with values obtained by equations of Table 7, with the coefficient of determination \(R^2\) of around 0.99.

2.3.3. Verification of correlation-based models for the normal and defrost operations

The verification of correlation-based models for the normal and defrost operations is made by comparing the predicted supply air humidity \(w_2\) with measurements from reference [23] under the same initial supply air temperature when the outdoor air temperature \(T_1\) is -20°C (Figure 11).

For conditions that are different from those in Table 7, the predicted supply air humidity \(w_2\) is in good agreement with the comparison of predicted supply air humidity \(w_2\) from the correlation-based models during normal operation and experimental results of reference [23] at outdoor air temperature of -20°C.

Equations 7 and 8 and coefficients \(A = 0.0\) and \(B = 1.16489\) that are obtained from data of [23] at -20°C of outdoor air temperatures. As shown in Figure 12, the predicted supply air humidity \(w_2\) is in good agreement with the experimental results from [23] with \(R^2 = 0.99\).

3. Simulation results and analysis

The effect of single core operation of ERV unit on the energy use of the NZEH house model is evaluated for three arctic locations (Inuvik, Kuujjuaq and Resolute) and Montreal. The heating season is defined as follows: from October 17 to May 1 (Montreal), from September 5 to June 4 (Kuujjuaq and Inuvik), and the entire year (Resolute).

As an example, this section presents the simulation of energy use of NZEH house model located in Inuvik, using the ERV unit with the manufacture’s defrost schedule. The total annual energy use for space heating of the NZEH house is 30,710.34 kWh, which is not affected by the ventilation heating by the heating coil (Table 8). Without the ERV unit, the ventilation heating
of the heating coil uses 14,863.22 kWh, which is reduced by 77% by the use of ERV. A summary of energy uses and defrost hours for all four locations are provided in Table 9. In general, the introduction of the ERV unit made a significant contribution to the total heating demand reduction of the NZEH house, ranging from 23% in Montreal to 25.17% in Inuvik. The ERV unit used in NZEH leads to greater ventilation heating energy savings (heating coil) under the arctic climate (from 75% to 79% in Kuujjuaq, Resolute and Inuvik) than in the cold climate of Montreal with 73% savings. Compared to the minimum standard requirements, the outdoor airflow rate due to defrost is reduced by 4.7% (223 hours) in Montreal, 19% (1043 hours) in Inuvik, 13% (701 hours) in Kuujjuaq, and 24% (1379 hours) in Resolute. The radiant heating energy uses per heated floor for the entire heating season are 74.8 kWh/1865/g2870 in Montreal, 147.64 kWh/1865/g2870 in Inuvik, 127.76 kWh/1865/g2870 in Kuujjuaq and 202.7 kWh/1865/g2870 in Resolute. Figure 13 presents the house humidity ratio (average) with and without ERV. It can be seen that due to the moisture exchange inside the ERV unit and moisture from the melted ice during the defrost operation, the house humidity ratio increased in all four locations (Montreal, Inuvik, Kuujjuaq and Resolute) when comparing with the case without ERV, e.g., the average humidity ratio in Jan in Inuvik increased from 1.7 g/kg to 4.9 g/k.

Table 8: Total annual energy consumption (ventilation heating by heating coil and space heating) of the NZEH house in case with and without ERV unit in Inuvik

| Months | Defrost hours | Radiant heating demand (kWh) | Ventilation heating by heating coil (kWh) | Total heating (kWh) | Radiant heating demand (kWh) | Ventilation heating by heating coil (kWh) | Total heating (kWh) | Total energy savings (kWh) |
|--------|---------------|-------------------------------|------------------------------------------|-------------------|-------------------------------|------------------------------------------|-------------------|----------------------------|
| Sep.   | 0             | 1631                          | 233                                      | 1865              | 1631                          | 761                                      | 2392              | 527                        |
| Oct.   | 57.73         | 2861                          | 354                                      | 3216              | 2861                          | 1364                                     | 4225              | 1009                       |
| Nov.   | 162.52        | 3731                          | 392                                      | 4124              | 3731                          | 1840                                     | 5572              | 1447                       |
| Dec.   | 191.41        | 4301                          | 449                                      | 4751              | 4301                          | 2118                                     | 6420              | 1668                       |
| Jan.   | 191.79        | 4517                          | 458                                      | 5075              | 4517                          | 2219                                     | 6736              | 1760                       |
| Feb.   | 169.51        | 4019                          | 414                                      | 4434              | 4019                          | 2197                                     | 6736              | 1760                       |
| Mar.   | 175.49        | 4149                          | 429                                      | 4579              | 4149                          | 2032                                     | 6181              | 1602                       |
| Apr.   | 93.48         | 3233                          | 350                                      | 3883              | 3233                          | 1507                                     | 4740              | 1156                       |
| May.   | 1.11          | 2169                          | 283                                      | 2452              | 2169                          | 964                                      | 3134              | 681                        |
| June   | 0             | 174                           | 21                                       | 196.11            | 174                           | 75                                       | 250               | 54                         |
| Total  | 1043.06       | 30710                         | 3389                                     | 34099             | 30710                         | 14863                                    | 45573             | 11473                      |

Table 9: The comparison of the energy consumptions (ventilation heating by heating coil and space heating) and defrost hours under three arctic climate (Kuujjuaq, Resolute and Inuvik) and one cold climate (Montreal) in the NZEH house

| Locations | Radiant heating demand (kWh) | Ventilation heating demand (kWh) | Total heating demand (kWh) | Defrost frequency (hours) | Ventilation heating demand (kWh) | Total heating demand (kWh) | Total energy savings (kWh) |
|-----------|------------------------------|----------------------------------|---------------------------|---------------------------|---------------------------------|---------------------------|---------------------------|
| Montreal  | 15566                        | 1938                             | 17504                     | 223.35                    | 7172                            | 22739                     | 6047                      |
| Resolute  | 42163                        | 4794                             | 46958                     | 1379.08                   | 20163                           | 62326                     | 4089                      |
| Inuvik    | 30710                        | 3389                             | 34099                     | 1043                      | 14863                           | 45573                     | 11473                     |
| Kuujjuaq  | 26574                        | 3087                             | 29661                     | 702.5                     | 12599                           | 39173                     | 2314                      |

4. Conclusion

The ERV combined with recirculation defrost has been recognized as the most adequate ventilation strategy in extremely cold climates. To overcome the limits of the existing models (Type 667b) of the ERV unit in TRNSYS, the correlation-based models of supply air temperature and humidity ratio of the ERV unit during the normal and defrost operation are developed by taking into account the effect of frosting and defrosting. The energy impact of the ERV unit with the recirculation
defrost on the NZEH house is investigated by integrating the correlation-based models into TRNSYS. Four cities are selected, three (Inuvik, Kuujjuaq and Resolute) located in the extremely cold climate and one (Montreal) in a cold climate as reference. Compared with the case without the ERV unit, the ERV unit can significantly reduce the heating demand of the house for all locations, with Inuvik having the highest energy saving by 25.7%. The ERV unit makes a considerable contribution to the humidity ratio increase for all four cities with a maximum increase from 1.7 g/kg to 4.9 g/kg in Inuvik.

Further work will focus on the energy impact of different defrost schedules and defrost threshold temperatures of ERV.

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