DEVELOPMENT OF A PROGRAM FOR ESTIMATING AIR-TO-AIR SENSIBLE HEAT RECOVERY ENERGY SAVINGS REDUCTION DUE TO FROST CONTROL AND COMPARISON WITH EE4

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ABSTRACT

The principal thrust of this research is to present a more realistic algorithm for estimating energy savings in relation to sensible air-to-air heat recovery accounting for two types of conventional frost control methods: face and bypass and outdoor air preheat. This algorithm was developed into a computer program called HRSIM that performs hourly calculations and is compared with the building simulation program called EE4 that is based on DOE2 and contains an option for air-to-air heat recovery. Results from the simulations indicate that the annual energy savings calculated in EE4 are significantly higher than HRSIM when accounting for frost control.

INTRODUCTION

Air-to-air heat recovery constitutes one of the most significant energy saving measures in new or existing buildings, occupying in some cases 15% or more of the total energy savings of a building when 100% outdoor make up air units are used. Building owners typically assess the feasibility of implementing heat recovery based on the estimated annual energy savings and financial incentives offered by utility companies and government programs.

In cold climates air-to-air heat recovery for HVAC applications (non-process) is limited by frost formation and fouling on the exhaust air-leaving side of the heat exchanger that can cause excessive pressure drops thus decreasing airflow. In its most destructive form, frost accumulation leads to ice build-up that can cause a catastrophic failure resulting in a ruptured heat exchanger. Conventional methods of frost control, such as outdoor air preheat and face and bypass dampers, will cause a reduction in annual heat recovery energy savings during the heating season. There is scant research on this topic. Besant and Simonson discuss frost control in relation to enthalpy wheels in several papers. M.R. Bantle (1987) is the only researcher known to the present author that specifically studies frost control both experimentally and theoretically on an air-to-air plate type heat exchanger. Total annual heat recovery energy savings accounting for frost control is not included in his research.

There are several building simulation programs that include an option for air-to-air heat recovery. In this paper the methodology for estimating heat recovery energy savings in the program EE4, the main building energy modeling tool used in Canada, will be examined. EE4 is used in conjunction with the Model National Energy Building Code (MNEBC) to evaluate building energy performance for the Commercial Building Incentive Program (CBIP) and is the basis for calculating the resulting financial incentives for building owners.

The first section of the paper reveals the methodology behind HRSIM. The two principal models that are used for developing the algorithm are presented. The main assumptions are listed and the fundamental equations are explained. A brief section is provided to describe the methodology used in EE4 to calculate heat recovery energy savings. The third section is dedicated to describing the simulations and presenting the corresponding results.

HRSIM – PROGRAM DESCRIPTION

HRSIM contains two principal modules.

1-Weather and schedule,

2-Heat Recovery

Weather and schedule module:

The weather and schedule module is executed first and allows the user to choose among various cities in North America and the corresponding 24 hour, 7 day schedule operation of the heat recovery system. CWEC weather data is used as the basis for Canadian cities. Weather data is extracted from the CWEC or TMY2 city file based on the operating schedule and the choice of three defined seasons: heating, free cooling, and cooling. The user has the choice to select among 4 combinations of seasons. The dry bulb temperature input from the weather file, T_{wi} : for the seasons is selected based on the economiser cooling set point, $T_{ec,sp}$, and the upper economiser set point, $T_{ecu,sp}$. The allowable season combinations and the corresponding temperature range selection criteria are identified as follows:

1. Heating only: $T_{wi} < T_{ec,sp}$
2. Cooling only: $T_{wi} \geq T_{ec,sp}$
3. Heating: $T_{wi} < T_{ec,sp}$

   and cooling: $T_{wi} \geq T_{ec,sp}$
4. Heating, free cooling, and cooling:

   $T_{wi} < T_{ec,sp}$, $T_{ec,sp} \leq T_{wi} < T_{ecu,sp}$, and $T_{wi\,i} \geq T_{ecu,sp}$

Option 4 represents weather data for the entire year, 8670 hours.

The schedule option allows the user to choose any regular start time and stop time for any number of days of a week. The weather and schedule input module also tracks the number of hours for the heating, cooling and free cooling seasons. The data for this module is extracted from the weather file and stored in a temporary work sheet.

Heat recovery module – main features:

The heat recovery module will use the weather data input file for the hourly calculation of heat recovery. The principal features of the heat recovery module include:

1- Calculation of effectiveness, ε, based on the NTU method for sensible heat recovery plate type heat exchangers.

2- ε is calculated for counter-flow and three types of cross-flow configurations.

3- Heat recovery is calculated on an hourly basis.

4- Choice of preheat or face and bypass frost control.

5- ε is calculated through a converging iterative method during face and bypass frost control mode.

6- Economiser option prevents overheating of supply air.

7- Annual heat recovery energy savings is calculated accounting for frost control and extra supply/exhaust fan power to overcome static pressure of the heat recovery device.

8- Annual auxiliary heating and cooling energy is calculated.

Heat recovery module – models:

Two variations of the model developed for the program are presented schematically in figures 1 and 2. Both models are identical except for the method of frost control. The first model illustrates the use of an electric preheat coil for frost coil. A glycol hot water preheat coil could also be used. However, the parasitic losses associated with the power consumption of the pump are not presently considered in this program.

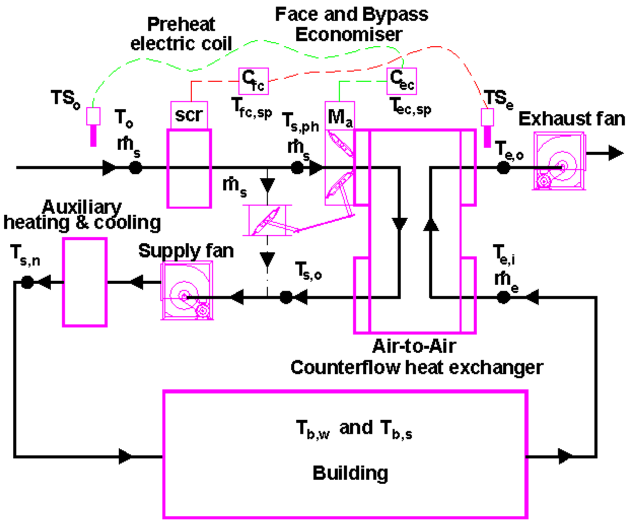


Figure 1.Schematic of a heat recovery system using pre-heat frost control

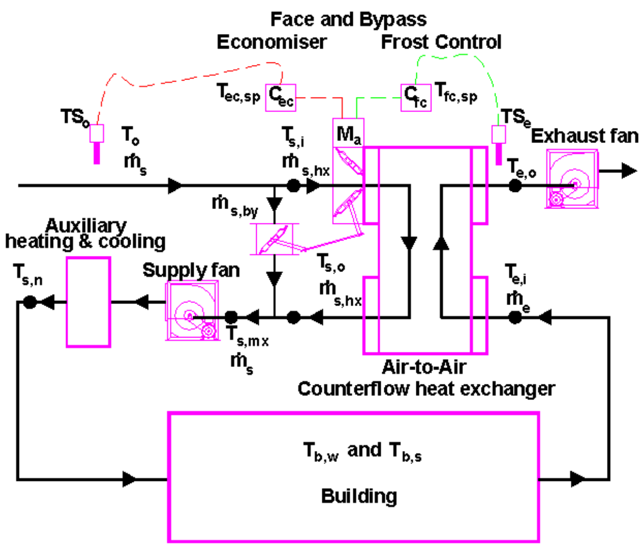


Figure 2.Schematic of a heat recovery system using face and bypass frost control

The second model contains a face and bypass damper for frost control. Both models contain face and bypass dampers for the economiser mode and are controlled by the outdoor air temperature. During the economiser mode, 100% of the outdoor air bypasses the heat exchanger.

A counter-flow heat exchanger is presented in figures 1 and 2 but the same model applies equally to cross flow heat exchangers. The variables presented in the above schematics are defined in the nomenclature section.

Heat recovery module – main assumptions:

The objective of HRSIM as mentioned earlier is to provide a more realistic estimation of annual heat recovery energy savings. However, there are several underlying assumptions that are made to simplify the model and calculations without sacrificing accuracy. Prior to describing the program in detail, the main underlying assumptions are revealed as follows:

1- The exhaust air transfer ratio (EATR), and the outdoor air correction factor (OACF) that represents air leakage through the heat exchanger from supply to exhaust or vice versa is considered negligible in the present study.

2- Frost accumulation is assumed negligible during the frost control mode, and thus the influence of frost formation or condensation on heat transfer in the heat exchanger is also considered insignificant.

3- Supply and exhaust static pressure drops across the heat exchanger were assumed for the given airflow based on the author's experience of actual on-site and laboratory measurements.

4- The static pressure drop across the supply and exhaust side of the heat exchanger is assumed to be constant even during the face and bypass frost control mode.

5- Variations in airflow due to elevation are considered negligible for the cities used for the calculations.

6- Bypass mass airflow rate during frost control mode is assumed to be steady state.

This list of assumptions is not exhaustive, and other minor assumptions are stated further on in the paper.

Heat recovery module – underlying algorithm and equations:

The first step in the heat recovery module input section is to choose the type of plate type heat exchanger. There are four configurations that can be chosen:

A- Cross-flow with both flows mixed

B- Cross flow with $C_{\min}$ unmixed and $C_{\max}$ mixed

C- Cross flow with both flows unmixed

D- Counter flow

The program will calculate the heat exchanger effectiveness, ε, based on the $NTU-\varepsilon$ method developed from Kays and London (1984). As shown in equation (1), ε is a function of the overall heat transfer coefficient, U, the heat transfer surface area, $A_{hx,ht}$, and the air streams containing minimum heat capacity, $C_{\min}$, and maximum heat capacity, $C_{\max}$.

$$\varepsilon = f(U, A_{hx,ht}, C_{\min}, C_{\max}) \quad (1)$$

NTU is defined as follows,

$$NTU = \frac{U \times A_{hx,ht}}{C_{\min}} \quad (2)$$

The thermal resistance of the heat exchanger plate material is sufficiently small to be neglected since thickness of the material, t, is very thin, and the corresponding thermal conductivity, k_{hx}, is much higher than air. It will be assumed that the air is clean and does not cause fouling of the heat exchanger surface. Thus, thermal resistance as a result of fouling, R_f, will also be neglected. Therefore U is calculated based on the film coefficients only for the supply and exhaust side of the plate.

$$U = \frac{1}{\frac{1}{h_c} + \frac{1}{h_h}} \quad (3)$$

In order to calculate U and $A_{hx,ht}$, the relevant physical dimensions of the plate heat exchanger are required to be entered into the program.

C_s and C_e are used to establish $C_{\min}$ and $C_{\max}$ as follows:

$$C_s = c_{pa} \times \rho_a \times \dot{Q}_s \quad (4)$$

$$C_e = c_{pa} \times \rho_a \times \dot{Q}_e \quad (5)$$

where $C_{\min}$ is the less of and $C_{\max}$ is the greater of C_s and C_e respectively. The supply and exhaust airflow rates, $\dot{Q}_s$ and $\dot{Q}_e$, are entered by the user. The specific heat capacity of the air, c_{pa}, and the density, ρ_a, are assumed constant.

Heat recovery module – accounting for frost control:

The program uses three types of equations to calculate hourly heat recovery :

$$\dot{q}_{hr} = c_{pa}\rho_a \dot{Q}_s(T_{s,o} - T_{s,i}) \quad (6)$$

$$\dot{q}_{hr,fb} = c_{pa}\rho_a \dot{Q}_s(T_{s,mx} - T_{s,i}) \quad (7)$$

$$\dot{q}_{hr,ph} = c_{pa}\rho_a \dot{Q}_s(T_{s,o} - T_{s,ph}) \quad (8)$$

Equation (6) is the basic heat recovery formula without frost control. The supply air inlet temperature to the heat exchanger, $T_{s,i}$, is assumed to be the same as the outdoor air temperature, T_o. The only unknown variable in equation (6) is the supply air outlet temperature from the heat exchanger $T_{s,o}$. It is calculated based on the formula for sensible ε from ASHRAE Standard 84-1991, and re-arranged to solve for $T_{s,o}$:

$$T_{s,o} = T_{s,i} + \varepsilon \times \frac{\dot{m}_{\min}}{\dot{m}_{s,hx}}\left(T_{e,i} - T_{s,i}\right) \quad (9)$$

Effectiveness can also be calculated based on the ΔT_e on the exhaust side of the heat exchanger, assuming that ε is the same for both the supply and exhaust side. Thus ε can also be expressed as follows:

$$\varepsilon = \frac{\dot{m}_e\left(T_{e,o} - T_{e,i}\right)}{\dot{m}_{\min}\left(T_{e,i} - T_{s,i}\right)} \quad (10)$$

The exhaust air inlet temperature to the heat exchanger, $T_{e,i}$, is entered by the user for both winter and summer conditions. The minimum mass flow rate, $\dot{m}_{\min}$, is the lower value between $\dot{m}_s$ and $\dot{m}_e$.

Equation (7) is the formula for calculating heat recovery during face and bypass frost control mode. The unknown in this equation is the mixed air temperature, $T_{s,mx}$, that is calculated based on the weighted average of the air bypassing the heat exchanger and the supply air outlet temperature from the heat exchanger. The corresponding equation is as follows:

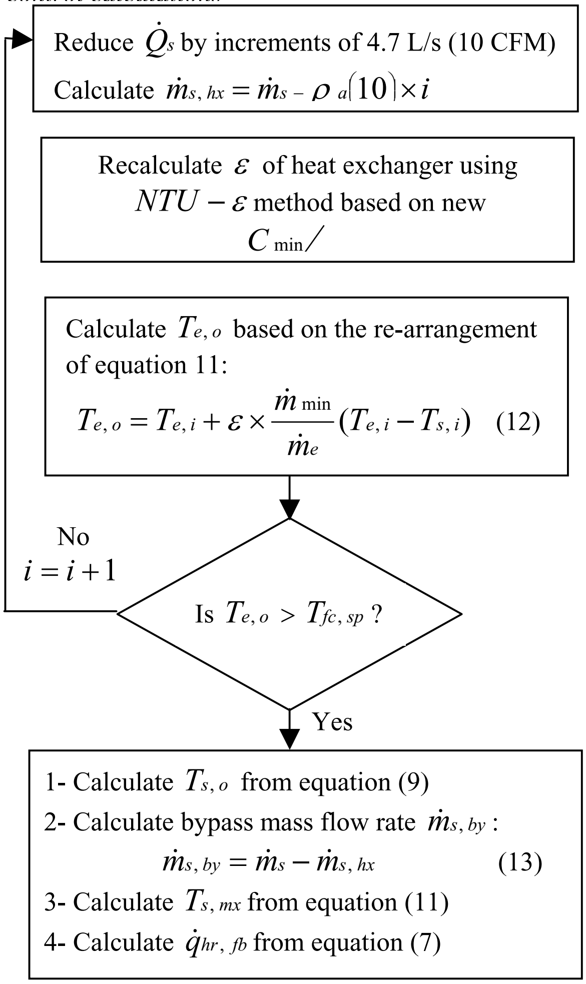
$$T_{s,mx} = \frac{\left(\dot{m}_{s,by} \times T_o\right) + \left(\dot{m}_{s,hx} \times T_{s,hx}\right)}{\dot{m}_s} \quad (11)$$

Equation (11) introduces three unknown variables, the bypass air mass flow rate, $\dot{m}_{s,by}$, the corresponding remaining mass flow rate passing through the heat exchanger, $\dot{m}_{s,hx}$, and the supply air outlet temperature from the heat exchanger, $T_{s,hx}$.

Prior to deriving the formulas for these variables the criteria for controlling the prevention of frost formation on the exhaust side of the heat exchanger will be described. As depicted in figure (2), a temperature sensor located on the exhaust air leaving side of the heat exchanger, TS_e, is connected to the frost controller, C_{fc}, that controls the modulation of the face and bypass dampers. The frost control set point of the controller, $T_{fc,sp}$, is entered by the user as an input to the heat recovery module and is usually a minimum of a couple of degrees Celsius above zero. It is this variable that is used to calculate the amount of bypass mass airflow rate, $\dot{m}_{s,by}$, necessary to prevent the exhaust air outlet temperature from the heat exchanger from dropping below $T_{fc,sp}$.

An iterative calculation in the program is performed as follows:

Figure 3. Flow chart for face and bypass frost control calculations



Equation (8) is used to calculate hourly heat recovery during pre-heat frost control mode. Pre-heat frost control functions by raising the supply inlet temperature, $T_{s,i}$, above the minimum temperature that will cause frost to form on the exhaust air-leaving side of the heat exchanger. This minimum temperature is referred to as the frost threshold temperature, $T_{f,th}$, and in HRSIM is a function of ε of the heat exchanger and the exhaust air inlet temperature, $T_{e,i}$. The effect of exhaust air relative humidity on frost formation is neglected in the present study. $T_{f,th}$ can be determined by evaluating $T_{e,o}$ from equation (12) for a range of $T_{s,i}$ starting from 0°C to –20 °C at 1°C intervals, and for a known ε until the following condition is reached.

When $T_{e,o} = T_{fc,sp}$, then $T_{s,i} = T_{f,th}$

Once $T_{f,th}$ has been determined, the pre-heat capacity can be calculated for each hour that $T_o < T_{f,th}$ from the following equation:

$$\dot{q}_{ph} = c_{pa}\rho_a \dot{Q}_s (T_{f,th} - T_o) \quad (14)$$

The total annual heat recovery energy savings for the two frost control methods is calculated as a summation of the hourly heat recovery for the entire year accounting for frost control based on the following equation:

$$E_{hr,fb} = \sum_0^{t_{hr}} \dot{q}_{hr} + \sum_0^{t_{hr,fb}} \dot{q}_{hr,fb} \quad (15)$$

In the case of pre-heat frost control the total heat annual heat recovery is as follows:

$$E_{hr,ph} = \sum_0^{t_{hr}} \dot{q}_{hr} + \sum_0^{t_{hr,ph}} \dot{q}_{hr,ph} \quad (16)$$

The total duration in hours for heat recovery with and without frost control, t_{hr}, $t_{hr,fb}$ and $t_{hr,ph}$ respectively, is tracked and used in equations (15) and (16).

The total annual heat recovery energy savings is reduced by the amount of fan power energy required to overcome the static pressure drop across the supply, p_s, and exhaust side, p_e of the heat exchanger. p_s and p_s are entered by the user. The equation used to calculate the total fan power energy consumption is described as follows:

$$Ef_{an,hr} = \sum_0^{t_{fan}} \left(\frac{\dot{Q}_s\, p_s}{eff_{f,s}\, eff_{m,s}} + \frac{\dot{Q}_e\, p_e}{eff_{f,e}\, eff_{m,e}} \right) \quad (17)$$

The fan power consumption is affected by the combined effect of the fan and motor efficiency on both the supply, $eff_{f,s}$ $eff_{m,s}$ and exhaust side, $eff_{f,s}$ $eff_{m,s}$ of the heat recovery unit. The total duration of the fans and motor operation will include the entire scheduled period as described in the weather and schedule module. The net total annual heat recovery energy savings can be calculated as follows:

$$E_{hr,fb,net} = E_{hr,fb} - E_{fan,hr} \quad (18)$$

$$E_{hr,ph,net} = E_{hr,ph} - E_{fan,hr} \quad (19)$$

The total heating energy consumption without heat recovery, E_{htg}, is calculated in equation (20) in order to provide a method of normalization of the heat recovery energy savings and serve as a basis of comparison for air-to-air heat exchangers with different ε, and frost control methods. It also represents the fraction of the total heating energy savings for a particular building.

$$E_{htg} = \sum_0^{t_{htg}} c_{pa}\, \rho_a \dot{Q}_s (T_{sn,sp} - T_o) \quad (20)$$

$T_{sn,sp}$ is the supply air discharge temperature that will enter the space in a neutral non-heating condition. In other words, it is assumed that the supply make up air does not perform the function of space heating. The normalized heat recovery energy savings for both face and bypass and pre-heat frost control is defined as follows:

$$S_{hr,fb} = \frac{E_{hr,fb}}{E_{htg}} \text{ and } S_{hr,ph} = \frac{E_{hr,ph}}{E_{htg}} \quad (21) \,\&\, (22)$$

EE4 – AIR-TO-AIR HEAT RECOVERY

The building simulation program EE4 was developed by the National Resources Canada as a compliance-checking tool for the Model National Energy Building Code (MNEBC) and the Commercial Building Incentive Program (CBIP). It is thus used as the basis for calculating the resulting financial incentives for building owners.

EE4 uses DOE2 as its calculation engine. The methodology used by EE4 to model air-to-air heat recovery is based on reducing outdoor air flow rate, $\dot{Q}_s$, by a fraction that represents the user entered heat recovery effectiveness, ε as shown in equation (23). The new airflow rate $\dot{Q}^*_s$ is used in place of $\dot{Q}_s$ to calculate the corresponding heating and cooling energy consumption of the ventilation air. In order to maintain the same original fan power consumption from $\dot{Q}_s$, EE4 raises the fan static pressure accordingly as depicted below.

$$\dot{Q}^*_s = (1-\varepsilon)\, \dot{Q}s \quad (23)$$

$$Pf_{an} = \frac{\dot{Q}_s\, p_s}{eff_{f,s}\, eff_{m,s}} = \frac{\dot{Q}^*_s\, p^*_s}{eff_{f,s}\, eff_{m,s}}$$

Therefore, solving for the adjusted static pressure:

$$p^*_s = \frac{\dot{Q}_s\, p_s}{\dot{Q}^*_s} \quad (24)$$

Based on the above methodology, EE4 does not account for frost control nor the reduction in energy savings associated with the extra fan power consumption to overcome the static pressure in the heat exchanger.

The financial incentive offered by the CBIP program is available for buildings that have been demonstrated to be 25% more efficient than a reference building in accordance with MNEBC. The corresponding financial incentive is 2 times the annual energy savings.

SIMULATIONS AND RESULTS

The heat recovery simulations and results of the present research are divided into two sections. In the first section several parameters of frost control will be studied. In the second section, a prototypical multi-residential building will be simulated in EE4 and compared with the results from HRSIM for the annual heat recovery energy savings.

Frost control parameters and their effect on heat recovery:

The frost threshold temperature, $T_{f,th}$, is a particularly important parameter since it indicates indirectly the capacity of the heat exchanger to operate during cold weather. Figure 4 illustrates the effect of different heat exchangers and their corresponding nominal ε on $T_{f,th}$. The results in figure 4 confirm the intuitive understanding that for heat exchangers with a higher ε, the capacity to cool down the exhaust air is also higher. Therefore, $T_{f,th}$ will be closer to freezing point for higher values of ε.

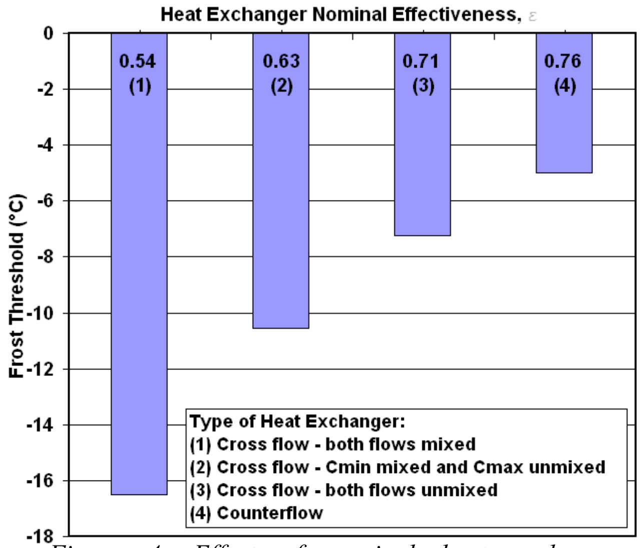


Figure 4. Effect of nominal heat exchanger effectiveness, ε, on frost threshold temperature, $T_{f,th}$

One of the unique features of HRSIM is the ability to re-calculate ε based on the amount of bypass mass airflow rate, $\dot{m}_{s,by}$. Figure 5 illustrates the variation of ε with the percentage of bypass, i.e. $\dot{m}_{s,by}/\dot{m}_s \, x100\%$ and the corresponding outdoor air temperature, T_o.

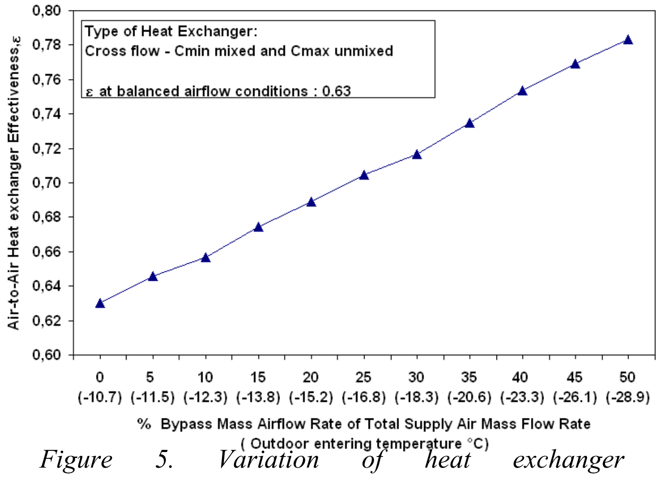


Figure 5. Variation of heat exchanger effectiveness, ε, with bypass mass airflow rate percentage and outdoor air temperature

As expected, when T_o becomes colder, there is a greater bypass mass airflow rate as response to the frost control. Greater $\dot{m}_{s,by}$ means less airflow through the heat exchanger causing unbalanced airflow conditions, which results in a higher ε. This has been experimentally validated during the author's research into cross flow heat exchangers in his Master's thesis (2004).

The frost control setpoint has significant implications in reference to annual heat recovery energy savings. This is clearly reflected in figure 6 that illustrates the variation of normalized heat recovery energy savings for different types of heat exchangers subjected to variations in $T_{fc,sp}$. From figure 6, it can be observed that heat exchangers with highest ε are more sensitive to variations in $T_{fc,sp}$, and vice-versa for the heat exchanger with the lowest ε. For example when $T_{fc,sp}$ is adjusted from 0 °C to 4.4 °C, the counter flow heat exchanger annual energy savings reduces to 21%, as compared with an 8.4% reduction in energy

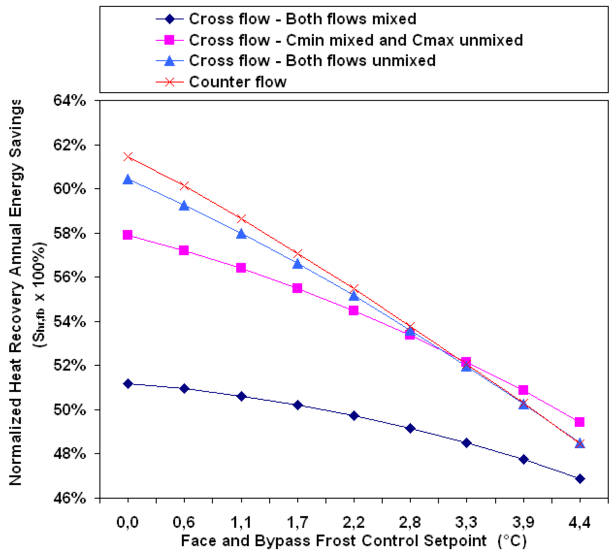


Figure 6. Variation of heat exchanger effectiveness, ε, with bypass mass airflow rate percentage and outdoor air temperature

savings for the cross flow heat exchanger when both flows are mixed. This figure has practical implications in terms of the placement and accuracy of the frost control sensor, TS_e, and the value of $T_{fc,sp}$. Both of these items should be checked at the commissioning stage of a project.

HRSIM heat recovery energy savings versus EE4:

A simple building model is developed in EE4 to obtain the annual heat recovery energy savings. The building modeled is a 3083 sqm four storey multi-residential building (MURB) with 32 units, and corridors on all four floors. The R-values for the walls, roof and floor were selected to be slightly higher than the MNEBC reference building. The high performance low emmissivity and argon-filled double-glazed windows were selected. High efficiency T8 flourescent lighting is used in the corridors. In reference to the HVAC units, a two pipe fan coil unit was selected, which represents a 100% outdoor air unit. The simulation was done for three cities: Montreal, Toronto, and Winnipeg. The simulation was run without heat recovery and then with four different values of ε: 0.54, 0.63, 0.71 and 0.76. HRSIM was run for the same values of ε with economiser, and with either face and bypass or outdoor air pre-heat frost control. EE4 provides two simultaneous sets of input and output files for every simulation. The first set of input and outputs, which is performed automatically by EE4, is the reference building designed for the minimum required energy performance in accordance with the MNEBC. The second set of input and outputs is for the proposed building. Figure 7 is a summary of all the simulations and presents a comparison between the reference building and the proposed building. The first case is the MURB without heat recovery. It has an average of 7% greater energy savings than the reference building. When heat recovery is included in the EE4 simulation, in most cases, the energy savings rise above 25% of the reference building. This would entitle the project for a financial incentive from the CBIP program. When the heat recovery savings is estimated in HRSIM and added to the proposed building energy savings, the increase in total building energy savings does not exceed 25% of the reference building. In this case, the project would not be entitled to a financial incentive.

It was found that the energy savings for heat recovery in EE4 is 10% to 53% higher than the energy savings calculated in HRSIM when accounting for frost control. Table 1 presents the implication of this difference in energy savings in terms of annual electricity costs for the different electrical utility rates.

Table 1
Annual electrical energy cost savings

		Annual energy savings cost comparison		
Nominal ε	Elect. Rate $/kWh	EE4 Heat Recovery	HRSIM w/ economiser and face and bypass frost control	HRSIM w/ economiser and preheat frost control
0,54	0,065	5 341 $	4 043 $	4 001 $
0,63		6 204 $	4 474 $	4 350 $
0,71		6 975 $	4 569 $	4 468 $
0,76		7 453 $	4 610 $	4 485 $
0,54	0,075	5 305 $	4 330 $	4 326 $
0,63		6 159 $	4 998 $	4 966 $
0,71		6 917 $	5 320 $	5 318 $
0,76		7 392 $	5 465 $	5 468 $
0,54	0,085	8 567 $	5 925 $	5 613 $
0,63		9 955 $	6 145 $	5 501 $
0,71		11 192 $	6 055 $	5 358 $
0,76		11 959 $	6 097 $	5 256 $

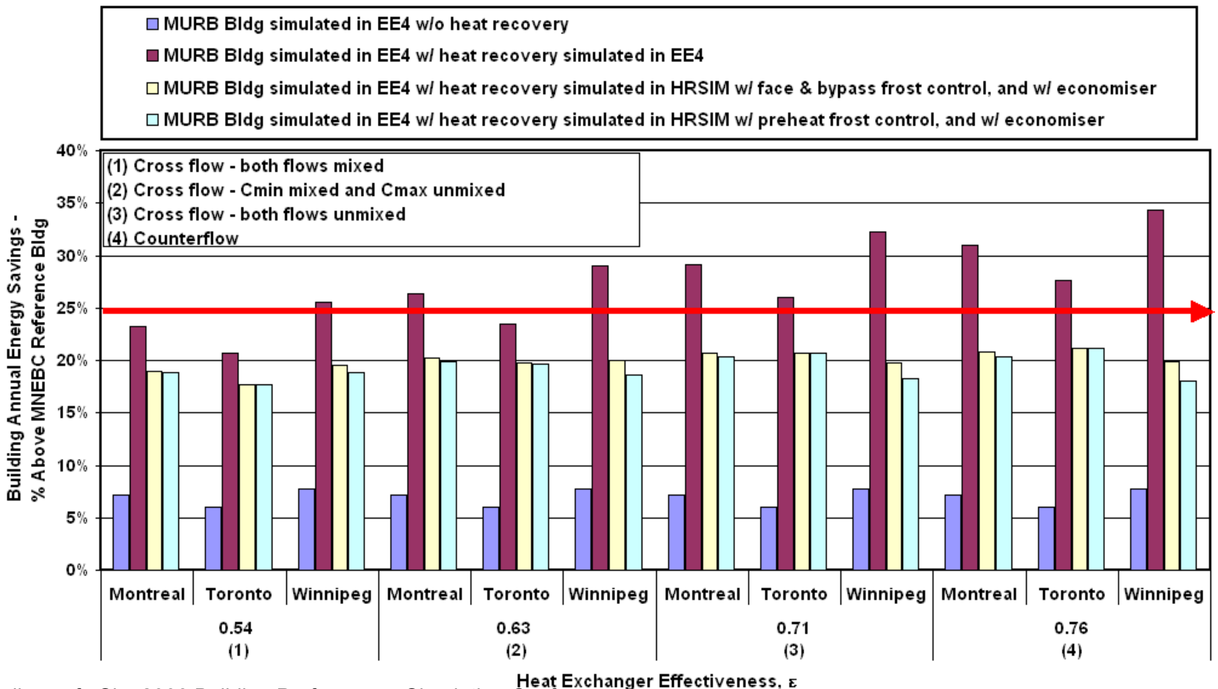


Figure 7. Annual energy consumption for MURB in comparison with MNEBC reference building

CONCLUSION

A computer program called HRSIM was developed to accurately estimate the annual energy savings using hourly calculations for sensible air-to-air heat recovery accounting for face and bypass and outdoor air pre-heat frost control. Energy savings calculated using EE4 were found to be between 10% to 53% higher than HRSIM when accounting for frost control.

NOMENCLATURE

$A_{hx,ht}$: heat transfer surface area
C_e : exhaust air heat capacity
C_{ec} : controller for the economiser
C_{fc} : controller for the frost control
C_{max} : maximum heat capacity
C_{min} : minimum heat capacity
c_{pa} : heat capacity of air
C_s : supply air heat capacity
ε : Heat exchanger sensible effectiveness
$eff_{f,e}$: exhaust fan efficiency
$eff_{m,e}$: exhaust fan motor efficiency
$eff_{f,s}$: supply fan efficiency
$eff_{m,s}$: supply fan motor efficiency
$E_{fan,hr}$: heat recovery fan power consumption
E_{htg} : total annual heating energy
$E_{hr,fb}$:total annual heat recovery energy (f & b)
$E_{hr,ph}$:total annual heat recovery energy (pre-heat)
h_c : heat transfer coefficient on cold side of hx
h_h : heat transfer coefficient on hot side of hx
k_{hx} : thermal conductivity of hx material
M_a : face and bypass damper motor
$\dot{m}_e$: exhaust air mass flow rate
$\dot{m}_{min}$: minimum air mass flow rate
$\dot{m}_s$: supply air mass flow rate
$\dot{m}_{s,by}$: supply bypass air mass flow rate
$\dot{m}_{s,hx}$: heat exchanger supply air mass flow rate
NTU :number of heat transfer units
ρ_a : density of air
p^*_s : adjusted supply air static pressure drop
p_s : supply air static pressure drop across hx
p_e : exhaust air static pressure drop across hx
P_{fan} : fan power
$\dot{q}_{hr}$: heat recovery rate no frost control
$\dot{q}_{hr,fb}$: heat recovery rate with face and bypass
$\dot{q}_{hr,ph}$: heat recovery rate with pre-heat
$\dot{q}_{ph}$: pre-heat rate
$\dot{Q}_e$: exhaust airflow rate
$\dot{Q}_s$: supply airflow rate
$\dot{Q}_s^*$: EE4 adjusted supply airflow rate
U : overall heat transfer coefficient
$S_{hr,fb}$: Normalized heat recovery savings f & b
$S_{hr,ph}$: Normalized heat recovery savings pre-heat
scr : silicon controlled rectifier
t_{htg} : total annual heating duration
t_{hr} : total annual heat recovery (no frost) duration
t_{fan} : total fan operation duration
$t_{hr,fb}$: total annual heat recovery (f & b) duration
$t_{hr,ph}$: total annual heat recovery pre-heat duration
$T_{b,s}$: air temperature in building space (summer)
$T_{b,w}$: air temperature in building space (winter)
$T_{e,i}$: inlet exhaust air temperature to hx
$T_{e,o}$: outlet exhaust air temperature to hx
$T_{ec,sp}$: economiser temperature set point
$T_{ecu,sp}$: upper economiser temperature set point
$T_{f,th}$: frost threshold temperature
$T_{fc,sp}$: frost control temperature set point
T_o : outdoor air temperature
$T_{s,i}$: inlet supply air temperature to hx
$T_{s,mx}$: supply mixed air temperature
$T_{s,n}$: neutral supply air temperature
$T_{sn,sp}$: neutral supply air temperature setpoint
$T_{s,o}$:outlet supply air temperature to hx
$T_{s,ph}$: supply air inlet temperature after pre-heat
T_{wi} :weather input dry bulb air temperature
TS_o :outdoor air dry bulb temperature sensor
TS_e :exhaust air outlet dry bulb temperature sensor

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