

# Feasibility Study of Multiple-Pass Total Energy Recovery Ventilator with Built-in Economizer Using TRNSYS: A Case Study for Toronto, Ontario

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## Abstract

This paper presents a feasibility study of an integrated heat and energy recovery ventilator (HERV) with a built-in economizer based on a case study for Toronto, Ontario. To achieve the assessment of such novel HVAC equipment, dynamic models were developed as components to be used in TRNSYS, along with a house model for the Archetype Sustainable House-A at The Living City Campus at Kortright. Simulation results revealed that the economizer control greatly improved the flexibility and competitiveness of the HERVs in summer. However, the HERV with a parallel-flow arrangement became inefficient during house heating, while the counter-flow approach was efficient at controlling both the temperature and humidity of the incoming air in order to meet the house demands. Overall, the HERV with a counter-flow arrangement could be a feasible option for Toronto.

## 1 Introduction

Many of our homes require year-round thermal control in order to maintain a comfortable living environment. In Canada, heating is almost always required in the winter to provide and maintain a comfortable living environment. Statistics show that space heating consumes approximately 62.6% of the total required energy in the residential sector (NRCan, 2013). As a result, modern houses (e.g., R-2000) have been increasingly built with advanced materials to achieve minimal heat loss and environment impact during operation (NRCan, 2013).

With the current leaning towards airtight energy-efficient houses, ventilation heat recovery becomes necessary for continuous mechanical ventilation, as well as reducing the energy use attributed to the outdoor air. Heat recovery ventilators (HRV) consist of a sensible core designed for sensible heat exchange, and provide no assistance to the regulation of humidity of the incoming air. Juodis (2006) emphasized that ventilation heat recovery will become completely useless when heat gains are enough to compensate all the losses and demands. Redundant heat recovery could potentially increase the cooling demand in summer, especially during periods of mild temperature outside. Energy recovery ventilators (ERV), on the other hand, consist of an enthalpy core that allows both sensible and latent heat to be transferred. It was evidenced that, ERV provides better overall performance than HRV under hot and humid condition by transferring some of the water vapor in the incoming air to the exhaust air (Ouazia, Julien, Swinton & Manning, 2006). However, it might not be true if the humidity in the house is not already ideal due to the lack of a dehumidifier. In this case, the ERV could potentially do more harm than good, i.e., the dryer incoming air is humidified by the exhaust air.

Currently existing HRVs and ERVs lack of flexibility to meet the demands of houses under different outdoor conditions. As a result, a versatile and flexible heat recovery ventilator is desired, which takes into account the deficiencies of the current designs and the potential of free-cooling.

## 2 Objective

The main objective was to investigate the feasibility of an innovative and versatile multiple-pass heat and energy ventilator (namely HERV), which was proposed to be used in the residential sector to provide better regulation of the ventilated air. Unlike the conventional HRVs and ERVs, the HERV consisted of two cores, with a sensible core assumed to be placed ahead of an enthalpy core. Chen et al. (2012) and Zhang et al. (in press) introduced and studied the potential of HERV in a parallel- and counter-flow arrangement using an Excel-based analysis tool, respectively. In this study, the potential of the aforementioned HERVs were further studied using transient simulation in order to derive some general conclusions for the proposed ideas. This paper consists of a short exposition of methodology, followed by a case study to explore the potential of the HERVs used in Toronto, Ontario.

## 3 Methodology

### *General Procedure*

Two dynamic models were created as components to be used in the transient simulation program TRNSYS, along with a house model. The parallel-flow model ( $HERV_p$ ) uses a constant effectiveness - minimum capacitance approach; the detailed descriptions of this method for air-to-air heat recovery device is given in the TRNSYS mathematical reference (Solar Energy Laboratory, 2012). The counter-flow ( $HERV_c$ ) was modeled in a similar manner, but iteration method was used to ensure air temperatures and humidity have converged during each time step.

### *House Descriptions*

The proposed HERVs were chosen to be simulated in the context of an airtight environment where mechanical ventilation plays a significant role for indoor air quality control – the Archetype Sustainable Twins-House A at The Living City Campus at Kortright. The house is a semi-detached residential house equipped with common technologies currently in the residential building market; it aims at demonstrating the potentials of reducing the amount of energy needed to sustain future housing (Dembo, Fung, Ng & Pyrka, 2010). The house has already been modeled as a TRNSYS Type-56 multi-zone building model (Safa, 2012); it contains four thermal zones corresponding to four floors of the house, all served by a two-stage variable capacity air source heat pump identical to the configuration in the actual building. The details of house specifications and mechanical equipment are listed in Table 1 to 3.

**Table 2: Structural features of the Archetype Sustainable House-A (Safa, 2012)**

<b>Features</b>	<b>Specifications</b>
Story	3 stories and 1 basement
Conditioned floor area	344.5 m <sup>2</sup>
Volume	986.1 m <sup>3</sup>
Airtightness	1.317 ACH at 50 Pa
Windows	2.19 W/m <sup>2</sup> K (0.39 Btu/hr-ft <sup>2</sup> -°F)
Above Grade Walls	RSI 5.31 (R30)
Below Grade Walls	RSI 3.54 (R20)
Roof	RSI 7 (R40)
Overall UA Value*	160 W/K

\*Heating at -7 °C outdoor and 21 °C indoor air based on TRNSYS House model

**Table 3: Mechanical system technical information (Barua, 2010; Zhang, Barua & Fung, 2011; Safa, 2012)**

Equipment	Specifications
Two-stage variable capacity air source heat pump packaged with AHU	Cooling capacity: 3.52 COP, 9.82 kW at 26.7 °C DB and 19.4 °C WB indoor, and 35 °C DB and 23.9 °C WB outdoor Heating capacity: 3.27 COP, 11.06 kW at 21.1 °C DB and 15.6 °C WB indoor, and 8.3 °C DB and 6.1 °C WB outdoor
Heat recovery ventilator (HVI Certified)	80% sensible recovery efficiency at supply air temperature 0 °C and net air flow 55 L/s

Simulation time step was chosen to be 1 minute, and the weather data file of Toronto, Ontario was used. According to the Köppen-Geiger climate type map for North America (Peel, Finlayson & McMahon, 2007), Toronto has a humid continental climate, with warm and humid summers, and cold winters. The inputs of heat gains for house can be categorized into four types: major appliances, interior lighting, occupants, and other appliances (see Table 3). These heat gains were equally distributed to each of the control zones. In addition, the dry-bulb temperature, relative humidity set points and air change rates for the simulation were respectively set to the following values:

- Zone 1 (basement):
  - Cooling season set points (May 20<sup>th</sup> ~ September 30<sup>th</sup>): cooling was off, and air change rate was 13.8 L/s.
  - Heating season set points (October 1<sup>st</sup> ~ May 19<sup>th</sup>): 21 °C, 30% and 13.8 L/s.
- Zone 2, 3 and 4:
  - Cooling season set points (May 20<sup>th</sup> ~ September 30<sup>th</sup>): 23 °C, 50% and 13.8 L/s per zone.
  - Heating season set points (October 1<sup>st</sup> ~ May 19<sup>th</sup>): 21 °C, 30% and 13.8 L/s per zone.

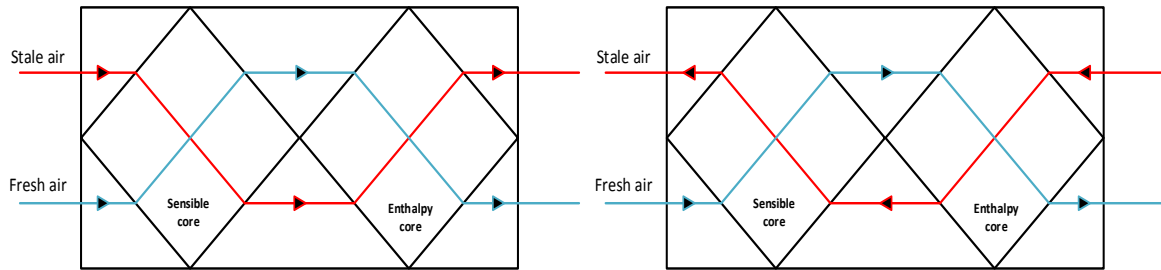
**Table 3: Heat gains from different internal sources (inputs of the ASH-A model)**

Heat Gain Type	Radiative Power (W)	Convective Power (W)
Major Appliances	0	250
Interior Lighting	62.5	62.5
Occupants	40	60
Other Appliances	0	125

### **Computer Modelling**

The HERVs were assumed to have an 80% effectiveness sensible core, followed by an enthalpy core that had 69% sensible and 45% latent effectiveness. In HERV<sub>p</sub>, the hot and cold airstreams enter the system at the same end and travel perpendicularly to one another through sensible and enthalpy cores (see Figure 1, left panel). The two airstreams in counter-flow arrangement enter

the system at a different end (see Figure 1, right panel). In addition, simulation was also conducted for HRV using TRNSYS model Type-760 with assumed sensible effectiveness of 80%, ERV (Type-667) that had 69% and 45% sensible and latent effectiveness.



**Figure 1: Simple scheme showing the flow arrangements: parallel-flow (left panel), counter-flow (right panel)**

The project scope requires the HERVs to be able to operate in four different modes: sensible, latent, dual-core and bypass modes. The sensible mode is dedicated to sensible heat recovery, that is, no moisture is exchanged throughout the process. This can be achieved by directing airflows completely around the enthalpy core. The latent mode, on the other hand, is dedicated to latent heat recovery by neglecting the sensible core. Although sensible heat is still recovered in the enthalpy core, it is not the point of interest. The dual-core mode, therefore, is desired only if both sensible and latent heat are needed to be recovered. The bypass mode is a control that allows the ambient cooler and dryer air to be directly ventilated to achieve free-cooling. The detailed information, design, and prototype of the HERV are presented by Olt et al. (2014).

### **Control Strategies**

In order to automate the operation modes defined in the last section, a detailed control logics were developed, as listed in Table 4. These control logics can be grouped into two sets: humidity-based and temperature-based. These controls were designed for the system to decide whether to use sensible core, enthalpy core or both cores for a given outdoor condition. According to the control logics, the sensible mode is activated only if conditions ( $T_3$  or  $T_4$ ) and  $H_1$  are met. In contrast, the latent mode is activated only if conditions ( $T_1$  or  $T_2$ ) and ( $H_2$  or  $H_3$  or  $H_4$ ) are met.

**Table 4: Control logics for the HERVs**

Control	Logic #	Control Logics	Sensible Core	Enthalpy Core
Humidity	$H_1$	$w_i > w_s$ & $w_i > w_o$		OFF
	$H_2$	$w_i < w_s$ & $w_i < w_o$		ON
	$H_3$	$w_i < w_s$ & $w_i > w_o$		ON
	$H_4$	$w_i > w_s$ & $w_i < w_o$		ON
Temperature	$T_1$	$T_i > T_s$ & $T_i > T_o$	OFF	
	$T_2$	$T_i < T_s$ & $T_i < T_o$	OFF	
	$T_3$	$T_i < T_s$ & $T_i > T_o$	ON	
	$T_4$	$T_i > T_s$ & $T_i < T_o$	ON	

There are many different ways of economizer control, however, an enthalpy-based control was chosen for this study. The combination  $T_2$  and  $H_1$  presented in Table 4 is an enthalpy-based control. However, it becomes insufficient if one decides to perform free-cooling at higher flow rate because it leads to higher latent load due to more air being needed to be dehumidified. Therefore, the following control logics were added to improve the control of the bypass mode:

$$H_o < H_s \ \& \ H_o < H_i$$

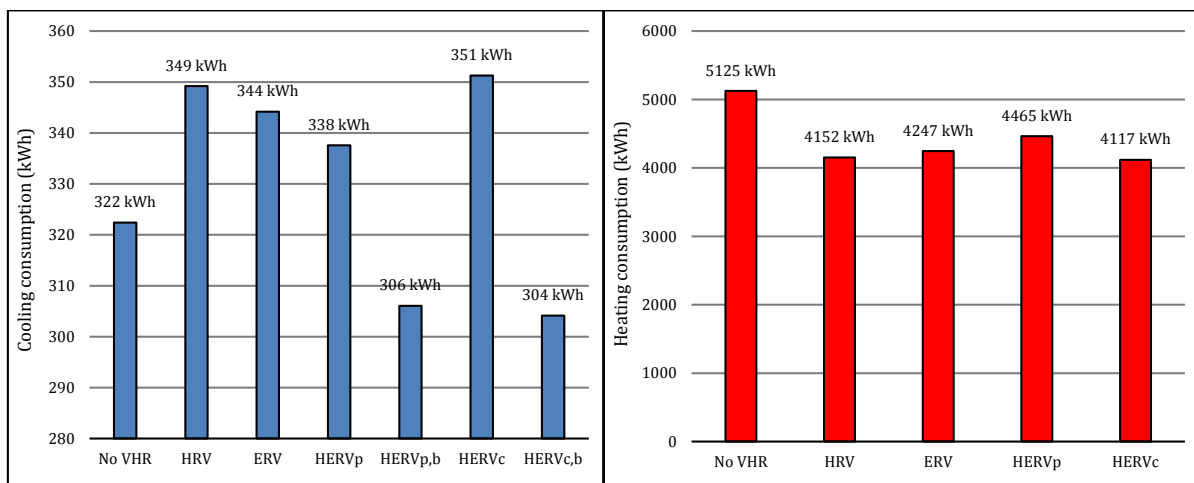
$$H_o > H_s \ \& \ H_o > H_i$$

## 4 Results and Discussion

### *Cooling and Heating Consumptions*

Figure 2 (left) illustrates the cumulative cooling consumption of the house in Toronto, Ontario that has a continental climate. The HRV and ERV-equipped homes consumed 349 and 344 kWh for cooling. In contrast, the house with direct ventilation consumed only 322 kWh, meaning that both the HRV and ERV were actually wasting energy, and hence, became redundant during the cooling period. The  $HERV_p$  and  $HERV_c$  resulted in 306 kWh and 304 kWh cooling consumption, respectively. In the meanwhile, the integrated bypass mode contributed to 32 kWh and 47 kWh savings, corresponding to 9.5% and 13.4% percent energy savings. Therefore, the integrated bypass mode with demand control improved the system's flexibility over the others.

Figure 2 right panel shows that the  $HERV_p$  house consumed 660 kWh less than the one that experienced direct ventilation. The saved amount was found to be 218 kWh less than the ERV that had low sensible effectiveness (69%). In contrast, both the HRV and  $HERV_c$  minimized the energy use attributable to outside air temperature. It is worth noticing that the sensible core of the  $HERV_c$  was given the priority for sensible heat recovery, but the nature of the enthalpy cannot be neglected, and hence, giving the system an advantage of enhanced sensible heat recovery during dual-core mode, even though it was not intended. Throughout the year, the  $HERV_p$  was found to be less efficient during house heating, while the  $HERV_c$  showed a greater flexibility towards the house cooling and heating in Toronto.

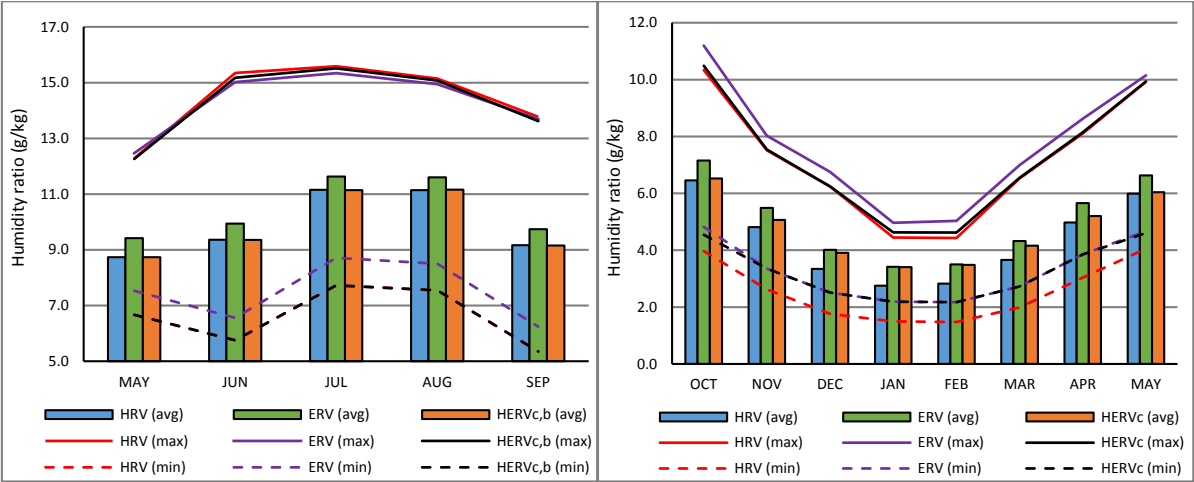


**Figure 2: Cumulative house cooling (left) and heating (right) consumption**

### *House Humidity*

The Archetype Sustainable House-A has neither a dehumidifier nor humidifier for humidity control, and hence, comparison was made using the house monthly humidity ratio. During the

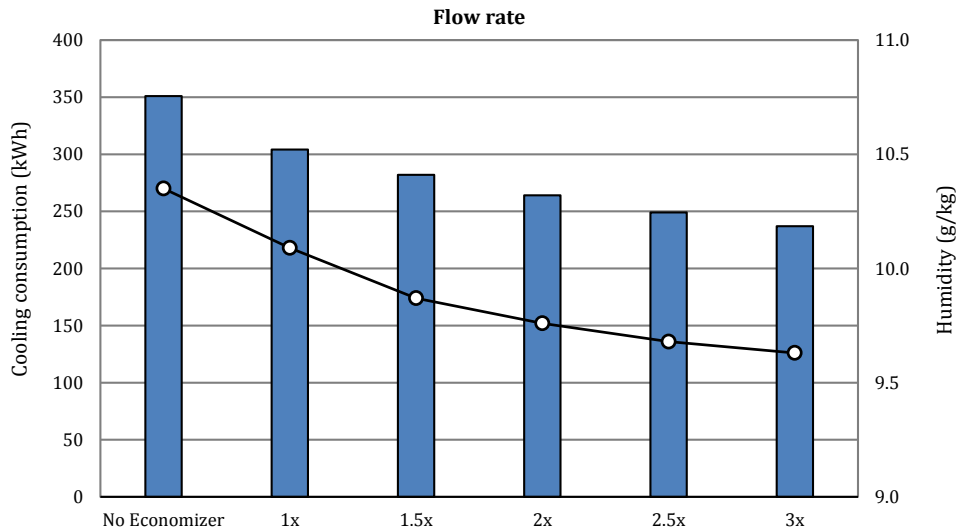
cooling period, the ERV house was found to have higher overall humidity than the HRV's (see Figure 3 left panel), that is, latent heat recovery was not needed/important. In comparison, the demand control allowed the humidity of the HERV<sub>c</sub> house to be better controlled, by directing air completely around the enthalpy core. For the heating period (see Figure 3 right panel), however, the HRV became insufficient during severe winter because the house was too dry, i.e., average humidity of the HRV house was 2.7 g/kg in January (equivalent to 17.6% relative humidity at 21 °C temperature). The ERV house can be temporary too humid, i.e., maximum humidity was 44% at 21 °C temperature. In contrast, for a given humidity set point, the HERV<sub>c</sub> controlled the process of latent heat recovery to seek a balance between the maximum and minimum humidity. This essentially improved the regulation of humidity of the incoming air. General speaking, the HRV house was not conducive to thermal comfort, while the ERV might have condensation problem during the cold winter months. Finally, the HERV<sub>c</sub> house was neither too dry nor too humid, and hence, reduced the chances of discomfort and interior window condensation.



**Figure 3: Humidity of the house during cooling (left) and heating (heating)**

***Free-cooling Energy Saving vs. Airflow Rate***

The effects of increased airflow rate during free-cooling on the cooling consumption was also investigated. Simulations were carried out by varying the flow rate from 1x (55 L/s) to 3x (165 L/s). Figure 4 illustrates the cooling consumption of the house at various flow rate in Toronto. The house consumed 351 kWh for cooling without the economizer control, with an average humidity of 10.4 g/kg. The consumption turned out to be 304 kWh while bypassing air at 55 L/s, and the average humidity reduced to 10.1 g/kg. As the flow rate increased by 1.5x, 2x and 2.5x, free-cooling contributed to a decrease in consumption of 69, 87 and 102 kWh respectively. On a yearly basis, it is clear that the energy savings gradually became lower as the flow rate increased. Therefore, the savings from free-cooling were not linearly related to the ventilation flow rate. Concisely, free cooling the house at high ventilation flow rate was not economical.



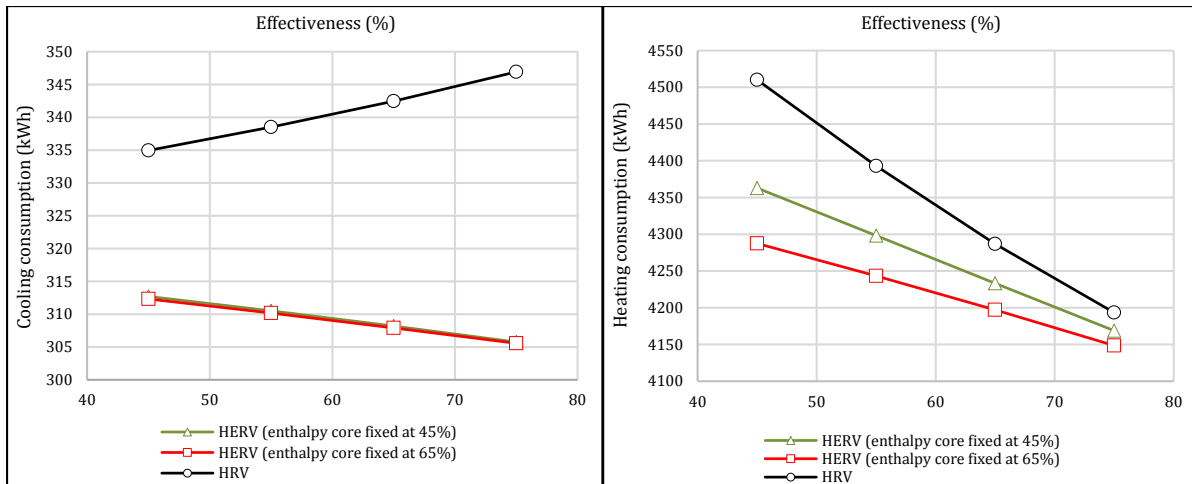
**Figure 4: Cooling consumption at different flow rate**

### *Energy Saving vs. Effectiveness*

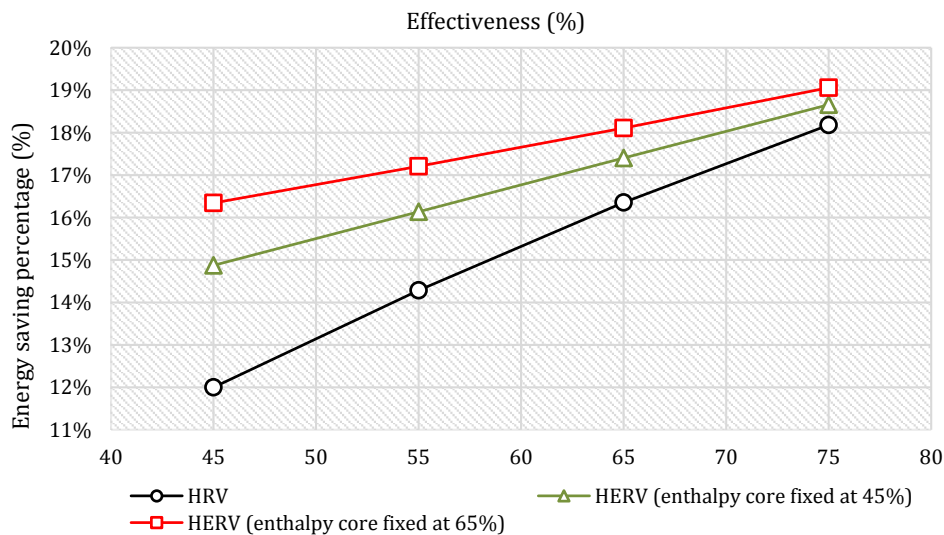
In the study presented by Liu et al. (2010), the ERV efficiency and saved energy percentage was found to be non-linearly related. To investigate the scale/degree of influence of core parameter on the overall performance of the HERV, simulations were carried out by varying the effectiveness of the sensible core from 45% to 85% with an increment of 10%. In the meantime, the effectiveness of the enthalpy core was fixed at certain point.

The cooling consumptions of the house at different effectiveness are illustrated in Figure 5 (left). The plot reveals that increasing the effectiveness from 45/45% to 75/45% resulted in a decrease in cooling consumption of 7 kWh. In addition, increasing from 45/65% to 75%/65% resulted in 6 kWh reduction. The minor change implies that a highly efficient core was not necessary for cooling because the savings were mainly attributed to the integrated bypass mode (no core). In conclusion, the economizer control was an effective approach for cooling when outdoor conditions permitted.

Figure 5 (right) presents the heating consumptions of the house at different effectiveness. The HRV house required 4510 kWh for heating at 45% effectiveness, and it dropped to 4193 kWh at 75%. In terms of percent energy savings, the increase in effectiveness resulted in 6.2% improvement, as shown in Figure 6. The consumption of the house with a  $HERV_c$  at 45/45% was 4363 kWh, and it was reduced by 194 kWh at 75/45%, corresponding to 3.8% percent saving. In addition, increasing from 45/65% to 75/65% resulted in 139 kWh reduction (or 2.8% percent saving). The additional savings attributed to the sensible core therefore reduced with an efficient enthalpy core.



**Figure 5: Cooling consumption (left panel) and heating consumption (right panel) at different effectiveness**



**Figure 5: Energy saving percentage at different effectiveness**

## 5 Conclusions

Two system models were developed to study the performance of the proposed HERVs for different climatic types. According to the obtained results, the following conclusions can be derived:

- The built-in economizer control was a feasible and beneficial option for cooling.
- Free-cooling at higher flow rate was not economical.
- The use of single core modes provided better control in humidity than the ERV.
- The  $HERV_p$  was infeasible during house heating.
- The  $HERV_c$  could be a feasible choice to satisfy the demands of the house under different outdoor conditions.
- Upgrading the sensible core for better regulation of incoming air temperature was found to be uneconomical when adopting an efficient enthalpy core.



The limitation of the presented study is the use of constant effectiveness, which may not well predict the behaviours of the HERVs because their performances depend on the difference between the indoor and outdoor air temperature/humidity. As a result, experiments will be conducted to obtain correlations for the prediction sensible and enthalpy effectiveness of the HRV and ERV that are currently being used in the Archetype Sustainable Twins-House. These correlations will then be implemented into the TRNSYS models to simulate the system characteristics based on the empirical effectiveness.

## 6 Acknowledgements

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## 7 Nomenclatures

H	enthalpy
$w$	humidity ratio
T	temperature
DB	dry bulb
WB	wet bulb
ASHP	air source heat pump
AHU	air handling unit
VHR	ventilation heat recovery

### *Subscripts*

$p$	parallel-flow
$c$	counter-flow
$b$	bypass
$i$	indoor
$o$	outdoor
$s$	set point

## 8 References

- Barua, R 2010, "Assessment and energy benchmarking for two Archetype Sustainable Houses through comprehensive long term monitoring". MASc thesis, Ryerson University, Toronto.
- Chen, CY, Mistry, J, Fung, AS, Leong, WH & Jhingan, S 2012, "Design and Analysis of an Integrated Heat and Energy Recovery Ventilation System with Economizer Control for Net-Zero Energy Solar Houses", *ASHRAE Transactions*, vol. 88, Issue 2, pp 82-89.
- Dembo, A, Fung, AS, Ng, KLR & Pyrka, A 2010, "The Archetype Sustainable House: Investigating its potentials to achieving the net-zero energy status based on the results of a detailed energy audit", *1<sup>st</sup> International High Performance Buildings Conference*, vol. 3247, pp. 1-8.
- Juodis, E 2006, "Extracted ventilation air heat recovery efficiency as a function of a building's thermal properties", *Energy and Buildings*, vol. 38, pp. 568-573.

- Liu, J, Li, W, Liu, J & Wang, B 2010, "Efficiency of energy recovery ventilator with various weathers and its energy saving performance in a residential apartment", *Energy and Buildings*, vol. 42, pp 43-49.
- Natural Resources Canada 2013, *Energy Use Data Handbook – 1990 to 2010*, Natural Resources Canada, viewed December 14 2013, <<http://oee.nrcan.gc.ca/publications/statistics/handbook2010/handbook2013.pdf>>.
- Natural Resources Canada 2013. R-2000 Protecting Our Environment, Natural Resources Canada, viewed December 14 2013, <<https://www.nrcan.gc.ca/energy/efficiency/housing/new-homes/r-2000/%205097>>.
- Olt, A, Zhang, JL & Fung, AS, "Feasibility Study of a Compact Residential HRV/ERV/Economizer Based Ventilation System", ASHRAE 2014 Annual Conference, Seattle, USA, June 28-July 2, 2014, Accepted for publication.
- Ouazia, BK, Julien, M, Swinton, MC & Manning, M 2006, "Assessment of the Enthalpy Performance of Houses Using Energy Recovery Technology", *ASHRAE Journal*, vol. 112, pp 26-33.
- Peel, MC, Finlayson, BL & McMahon, TA 2007, "Updated world map of the Köppen-Geiger climate classification", *Hydrology and Earth System Sciences*, vol. 11, pp 1633-1644.
- Safa, AA 2012, "Performance analysis of a two-stage variable capacity air source heat pump and a horizontal loop coupled ground source heat pump system", MAsc thesis, Ryerson University, Toronto.
- Solar Energy Laboratory 2012, *TRNSYS 17 Manual - Volume 4, Mathematical Reference*, University of Wisconsin-Madison, Madison.
- Zhang, DH, Barua, R & Fung, AS 2011, "TRCA-BILD Archetype Sustainable House – Overview of Monitoring System and Preliminary Results for Mechanical Systems", *ASHRAE Transactions*, vol. 117 issue 2, pp. 597.
- Zhang, JL, Fung, AS & Jhingan, S, "Analysis and Feasibility Study of Residential Integrated Heat and Energy Recovery Ventilator with Built-in Economizer Using an Excel Spreadsheet Program". *Energy and Buildings*, 2014, *in press*.