Parametric Analysis of Energy Recovery Ventilation Performance in the High Rise Residential Sector

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Abstract

The performance of energy recovery ventilation (ERV) units in high-rise residential buildings is analyzed. ERV's performance is evaluated by the amount of annual recovered sensible and latent heating and cooling energy. ERV's are typically rated by the applicable Standards under controlled operating conditions. The current literature identifies several factors that impact ERV performance under operating conditions, such as infiltration rates, ERV leakage flows, temperature set points, and flow control schemes. EnergyPlus is used to create a representation of a typical residential suite, through which the impacts of the parameters is studied. Initial performance of the ERV model is validated through comparison to collected temperature and relative humidity data from an installed, operational ERV unit in a high-rise condominium. Results indicate that leakage flows within the ERV represent the highest potential contributor to overall performance. Economizer control strategies are identified as a viable option for improving the ERV performance during summer and shoulder seasons.

1 Introduction

Design of energy efficient buildings has been one of the determining factors in the built environment. Airtight building envelope design has been a dominant tool to improve energy efficiency. With improved building air tightness, adequate ventilation has now become a competing priority in many modern building codes, demonstrated by the *ASHRAE 62.1* Standard series which stipulates minimum outdoor rates for occupied spaces (ASHRAE, 2007). In a cold climate, however, providing more fresh air equates to increasing the energy required for heating in the winter and cooling in the summer.

Typical high rise residential construction has utilized a corridor pressurization system as a means of both combating stack flows and providing ventilation air to suites. Airflows needed to create this positive pressure differential are significant, which is problematic in terms of the energy needed to heat or cool this air. More recently, high performance residential building have revised this strategy by providing fresh air via much smaller air handling units within each suite. As a result, the total volume of pressurization air per suite can be reduced, and therefore total energy consumption of the high-rise building is reduced as well.

In order to improve energy efficiency, the indoor units have utilized systems to recover heat, in the case of heat recovery ventilation (HRV), or heat and moisture, in the case energy recovery ventilation (ERV) by passing the exhaust air stream across the incoming supply air, providing a buffering effect to the incoming air. The performance of ERV devices in high rise residential condominiums is the primary focus of the current investigation. Complete details of the study are contained in Barker (Barker 2013).

Background information of ERV performance is presented in Section 2. An energy model is created of a typical ERV unit using the simulation software EnergyPlus. The simulation details are also described in Section 2. The evaluation of ERV performance in terms of recovered energy is briefly described in Section 3.

ERV units have been shown to be effective in reducing the heating and cooling load of the ventilation air in residential buildings through experimental analysis and modeling. Effectiveness, however, is often based on testing under laboratory conditions. In reality, many external factors can impact the operation of ERV units, and reduce their effectiveness under realistic operating conditions. Such factors include room infiltration (Roulet *et al.*, 2001; Manz *et al.*, 2001; Dodoo *et al.*, 2011), unbalanced airflows encountered through the ERV due to leakage (Roulet *et al.*, 2001; Manz *et al.*, 2001), unanticipated temperature set points (Kim *et al.*, 2012, Fernandez-Serea *et al.*, 2011, Zhou *et al.*, 2007) or operation of the unit (RDH Engineering, 2013, Santin *et al.*, 2009). As these issues are often presented in isolation, their relative significance under real world operating conditions is unclear. The main focus of the current study is to evaluate the impact of the four highlighted factors on the effective performance of ERVs in high rise residential units. The range of the parameters enumerated above is presented in Section 3.

The energy model is validated by using data from a long-term monitoring of field variables of an actual ERV unit in the Greater Toronto Area (GTA). Model validation is presented in Section 4.

Creating an energy model of a typical residential suite acts as a test bed in which the impacts of these factors can be analyzed and compared. In turn the impact on the ERV performance during peak periods and throughout the year can be quantified as a function of the highlighted factors. Comparative analysis was undertaken to further determine the relative significance of the investigated parameters. The details of the parametric analysis and the results are presented in Section 5.

2 Energy Recovery Ventilation Model

A general description of the ERV and its functionality are described in this section. To determine the ERV's energy performance, an energy simulation of a typical residential suite can be utilized. *Energy Plus,* the dynamic energy simulation engine, was used to determine the impacts of the parameters that control the ERV's performance. The simulation model is described in this section.

Mechanical System Description

The mechanical ventilation strategy of interest here is an in-suite ventilation system. A representation of the typical suite's mechanical layout is shown in Figure 1 below. In this strategy ventilation is provided directly to the suite via intake louvers located at the suite's balcony, passing through the ERV device. Ventilation air is then ducted directly to occupied spaces within the suite. The exhaust side of the ERV unit typically originates in the suite bathroom, and is exhausted through exhaust grilles at the suite's exterior wall. The ERV can either be ducted in series or in parallel with an in-suite fancoil unit, which provides heating and cooling as demanded by the thermostat. In the case analyzed here, the ERV is integrated within the fancoil unit, and so is ducted in series with the heating and cooling coil. The fancoil unit is served by hot water from a central boiler and chilled water from a chiller plant. Finally, the residential suite is compartmentalized from the corridor and rest of the building through weather-stripping and sealing of the suite's entry doors. Developers seeking to construct a 'high performance' residential building usually apply such a strategy to reduce the overall energy consumption of the building.

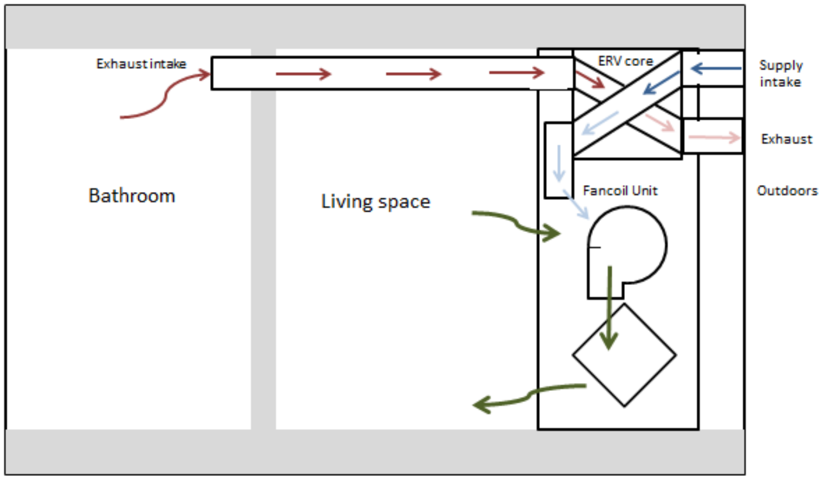

Figure 1 - In suite mechanical system layout

EnergyPlus Model

The typical suite was assumed to be approximately 74.3 m^2 (800 sq.ft), representing a one-bedroom condo unit for two person occupancy. The condo suite has a single exterior wall with window on one side, and five interior sides, assumed to be adiabatic. As the model represents a test bed and not an actual operating suite, steps were taken to estimate the loads and characteristics of the suite as per applicable standards. Therefore, typical modeling assumptions related to lighting, occupancy and power use schedules are applied. The initial inputs to the model represent the 'typical' operating conditions for infiltration, leakage, temperature set points and operation as defined in Section 3.

Published manufacturer's data was applied to properly simulate the performance of the ERV core. The manufacturer's data includes the ERV core's latent and sensible performance for a range of operating conditions, tested as per the AHRI Standard 1060. Published effectiveness of the ERV core, for two extreme flow rates, is shown in Table 1. The simulation models evaluate the ERV's performance in terms of the recovered sensible and latent energy.

Table 1 – Published ERV Core performance as per AHRI Standard 1060

	Summer Effectiveness		**Winter Effectiveness**	
Flow Rate (L/s)	Sensible	Latent	Sensible	Latent
18.87	73%	45%	73%	49%
47.17	63%	31%	63%	35%

3 ERV performance review

A considerable number of experimental or simulation studies are available in the literature, which have evaluated the impacts on building energy performance from ERV unit installation. Several parameters which influence actual ERV performance were also described in the literature. Influencing factors of interest are those which have real world connotations with regard to ERV performance in a high-rise residential setting. A review of these parameters, such as infiltration rate, ERV leakage, temperature set points and operating conditions, is presented in this section.

Standard performance evaluation of ERVs

The Air-Conditioning, Heating and Refrigeration Institute (AHRI) has developed and maintained Standard 1060, for *Performance Rating of Air-to-Air Exchangers for Energy Recovery Ventilation Equipment* (AHRI, 2005).

The AHRI provides calculation procedures to determine sensible and latent effectiveness of ERV cores. The sensible effectiveness is dominated by dry-bulb temperature. Latent effectiveness, meanwhile, is dependent primarily on the humidity ratio. The AHRI standard has also incorporated rating the proper construction of the unit by accounting for losses in airflow through leaks or cracks in the unit, referred to as the exhaust air transfer ratio (EATR).

Testing ERV performance under ideal laboratory conditions and balanced flow provides an adequate means of standardizing the playing field whereby the manufacturers state ERV unit performance characteristics. However, as a reflection of actual operating conditions, tested results may be inaccurate for various reasons. Several recent studies have been interested in the in-situ performance testing of ERV units in an attempt to determine their real world impact and these will be discussed subsequently.

The sensible recovery rate of the ERV can be determined at any time step using a simple mass flow equation by applying the incoming and leaving dry bulb temperatures of the ERV unit, as well as the mass flow rate and specific heat of air,. The latent recovery rate can be similarly determined by considering the incoming and leaving humidity ratio, and the latent heat of vaporization of water. One of the selected outputs of the *EnergyPlus* simulation is the hourly rates of sensible and latent recovery.

Infiltration

Roulet *et al*. (2001) point out that due to infiltration, the real heat recovery efficiency cannot equal the nominal heat recovery efficiency. Similar conclusions identify that ERV savings are maximized in a more passive building design with a tight envelope, compared to traditional construction methods (Dodoo *et al.*, 2011).

Air infiltration in high rise residential units can vary widely, dependent on numerous factors, including location and height within the building, exterior wall construction, degree of compartmentalization and wind patterns. Infiltration is typically determined through blower door testing run at high pressure differentials such as 50 or 75 Pascals. A recent extensive study was undertaken to characterize air leakage rates in several high-rise residential buildings in Canada (RDH Engineering, 2013). Air leakage data was compiled for 43 buildings, ranging in age from the mid 1950s to 2011. The overall average air leakage was shown to be 3.65 $L/s/m^2$ of exterior wall area at 75 Pa,, however the study further analyzes in isolation residential units which are compartmentalized, noting a leakage rate of around 1.67 $L/s/m^2$ at 75 Pa (RDH Engineering, 2013). In comparison, professional energy modeling assumes a nominal infiltration rate of 0.025 $L/s/m^2$, following Canadian modeling guidelines, which is a lower nominal rate than the tight building envelope analyzed here (NRCan, 2011). It is seen, therefore, the ERV performance as a function of the infiltration rate needs to be better understood, given this range.

ERV Unit Leakage

Parasitic airflows or unintended recirculation of air within the ERV units will further reduce the actual heat recovery effectiveness. As a result of poor design and/or construction, the parasitic flows can occur in a number of scenarios – including poorly sealed ductwork causing leakage, poor sealing of the ERV units themselves, directly interrupting the ERV performance, or external short-circuiting, where exhaust flows are located adjacent to air intakes (Roulet *et al.*, 2001).

A recent study has demonstrated three unintentional airflows in smaller ERV devices which play a role in performance: external flow of exhaust air into the fresh air supply due to proximity of supply and exhaust registers; mixing of supply air into the exhaust air within the ERV unit; and mixing of exhaust air into the fresh supply air within the ERV unit (Manz *et al.,* 2001). For the purposes of this study, external leakage flows will not be analyzed, as this leakage does not modify the flow through each side of the ERV core and into the unit. Nor will flows from the exhaust air stream to the supply air stream of the ERV core by considered. These flows are primarily of concern in relation to the impact of air quality entering the suite, as they represent the flow of exhaust air back into the suite. Impacts to indoor air quality from ERV unit cross contamination has been studied recently in the Toronto residential market (Parker, 2012), and therefore these issues are not considered here.

Flows from the supply to the exhaust side have been noted to be between 17% and 34% of nominal flow (Manz *et al.*, 2001). The mid-lower range of internal short circuiting flows defined can represent typical ERV construction. The higher internal short circuiting flows may represent more extreme cases where ERV construction is particularly poor. Finally, the *Passiv Haus Institut* will only certify ERVs which can demonstrate a leakage rate of 3% or less of the typical supply flow rate, representing a best practice in ERV construction (*PassivHaus Institut,* 2009). The *PassivHaus Institut*'s specified leakage rate will also be investigated as one of the parameters in this study. By comparison, professional energy modeling practice may not consider ERV leakage flows at all, depending on the purpose of the model, risking an overestimation of energy savings from the ERV.

Temperature Set Points

Fernandez-Seara e*t al*. (2011) analyzed the performance of plate type heat exchangers under experimental conditions, and the effect of varying outdoor temperature and humidity conditions. Their results showed a near linear relationship of declining recovery rates with increasing fresh air temperature under a heating condition. A concern therefore arises in residential buildings, as temperature is typically controlled by the individual tenant, with varying thermal comfort preferences, and there is ultimately very little influence from building managers and operators. Analysis has shown that higher set points can lead to ERVs becoming uneconomical, as this can lead to recovery of excessive heat in the cooling season, or vice versa in the heating season (Fernandez-Serea e*t al*., 2011). An example of this may occur during the night time in early summer.

As indoor temperature set points are highly dependent on the tenants individual comfort requirement, and hence difficult to determine for any given residential suite. Modeling standards such as the National Energy Code for Buildings (NECB) in Canada point to typical set point of 24°C during the cooling season, and 22°C in the heating season, with a setback to 18°C overnight (NRCan, 2011). It is seen that two different scenarios are possible. A tenant, who is more concerned with their utility bill, will extend these set points to be 26°C in the cooling season and 21°C in the heating season. Conversely, a tenant, more concerned with thermal comfort, will automatically set the thermostat to a constant 23°C year round.

ERV Control Strategies

While temperature set points are of potential significance to ERV performance, control of ERV units based on temperature set points is more typical in office rather than residential buildings. Rasouli *et al.* (2010) studied the impact of ERV operation in a range of climates, including cold climates. In their study, they noted a negative effect if ERVs are left uncontrolled in an office with a centralized HVAC system. In cold climates, if the ERV is operated during the summer, the unit may recover unwanted heat when the outdoor temperature falls below the room temperature, while the cooling loads remain due to internal and solar gains

(Rasouli *et al.*, 2010). Realizing that summer recovery is primarily influenced by latent recovery in a cold, humid region (such as Toronto), Rasouli *et al.* (2010) note that increasing latent effectiveness of the ERV will prolong beneficial operation of the ERV throughout the year.

However, ERV operational control is not practical in residential suites. Typical MURB ERV unit installations give users the capacity to turn on or off the ERV within their unit with a push button controller, often in conjunction with bathroom fan use. However there are no control strategies to operate the ERV automatically based on temperature or humidity differentials. Rather, ERV operation is often left to the discretion of the user, and any control is done manually by a tenant who may not have an understanding of ERV performance. An automated ERV controller may be warranted in residential suites, and its potential inclusion as a control options needs to be analyzed. In order to maintain ventilation rates, the ERV device must be equipped with a bypass, to allow economizer, or free cooling operation, when beneficial.

4 Validation

Before moving forward with the parametric analysis, a validation of the modeled ERV core is warranted. The validation exercise is undertaken to ensure that the modeled ERV unit, as described in Section 2, performs similarly in the energy model and under actual operating conditions. In this validation analysis, four main parameters related to ERV performance were considered to be of primary concern: winter sensible heat recovery, summer sensible heat recovery, winter latent heat recovery, and summer latent heat recovery.

To validate performance, an in-suite ERV currently installed in a residential suite in Toronto was outfitted with sensors to measure temperature (°C) and relative humidity (%) at four ports of the ERV. Measurement locations include: the supply air entering the ERV; the supply air leaving the ERV; the exhaust air entering the ERV; and, the exhaust air leaving the ERV. The supply and exhaust airflow were also measured, to determine whether or not the ERV is balanced. Measurements were taken at five minute intervals over the course of one heating and one cooling season. For each interval, outdoor temperature (°C) and relative humidity (%), indoor temperature set points and system status (i.e. heating or cooling mode) were also measured.

The in-suite system is similar to the one represented by the energy model as described above. Data collection for the purposes of the validation analysis took place over a period of approximately 7 months, from December 17th, 2012 to July 17th, 2013, while the unit was occupied. Outdoor dry bulb temperature ranged from -11°C to 35°C, and outdoor relative humidity ranged from 15% to 79%. This range of data is considered representative of a typical heating and cooling season in Toronto, and conditions in between.

Airflow measurement devices for the incoming supply and exhaust streams of the ERV were not operational during the measurement period. Therefore, the core temperature performance of the ERV can only be validated here assuming a balanced flow. It is also important to note that as only two airstreams were measured, the operating EATR and therefore the net effectiveness of the ERV core were not determined. And hence, validation analysis is limited to only the nominal temperature based performance and operation of the ERV. Core flow is assumed to be balanced for the purposes of the validation analysis.

Hourly analysis of data demonstrates that both sensible and latent measured recovery rates are comparable to the response seen in the energy model. Figure 2 and 3 demonstrate the winter sensible recovery and summer latent recovery response of the modeled and measured ERV. Figure 2 shows that as modeled dry bulb temperate increases in the winter, a corresponding decrease in recovery rate is seen. This follows the trend of the measured performance and dry blub temperature, shown in red. Absolute average modeled and measured rates of recovery as a function of dry bulb temperature correspond favourable as well, demonstrating significant overlap. In summer, latent recovery amounts to a drying effect on the humid incoming outdoor air, exchanged with the ostensibly drier conditions of the indoor environment, therefore buffering the humidity of the incoming air. Measured analysis shows similar increasing amount of recovery with high outdoor humidity levels. Measured and modeled latent recovery does not overlap, explained by an absence of equipment used to directly control humidity in suite. Indoor humidity at specific outdoor humidity ratios in the modeled and monitored suite was more difficult to reconcile, as it may be dependent on specific occupancy rates, or indoor activities such as showering or cooking, and use of additional exhaust fans. Given the range of tenant behaviour possible, these processes are not considered in the model and do not necessarily represent the monitored suite. However, the recovery rate trend is similar.

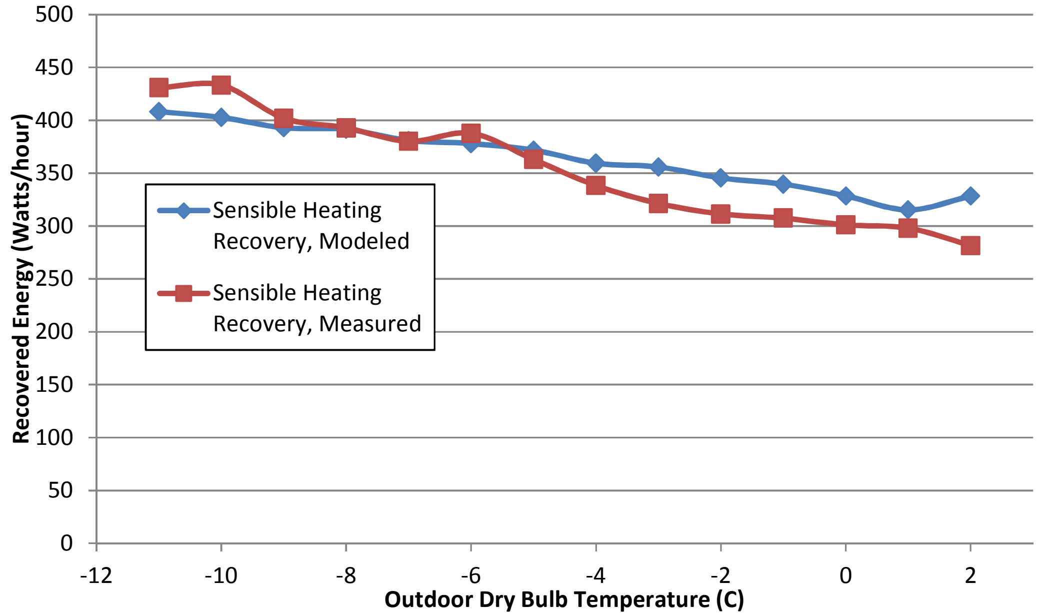

Figure 2 - Winter sensible recovery

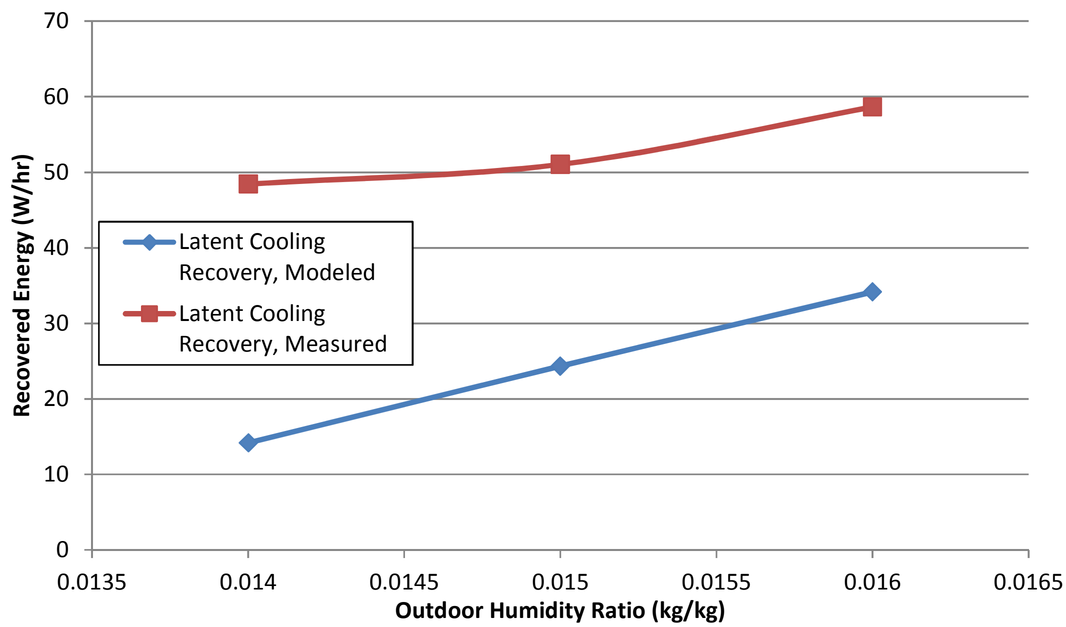

Figure 3 - Summer latent recovery

The comparison between modeled and measured recovery rate shows that the simulation is able to explain the performance behaviour of the ERV. It is seen therefore that simulation results can realistically evaluate the results of the parametric analysis of the modeled ERV. Results of the parametric analysis are presented in the following section.

5 Parametric Analysis – Results and Discussion

Four parameters were found to be of interest and were described in Section 3. Eight different cases were investigated so as to evaluate the impacts of the above four parameters, and are:

1. Baseline scenario: typical infiltration rate of 1.67 L/s/m^2, at 75 Pa, typical leakage of 17% of supply flow, typical temperature set points, uncontrolled ERV operation.
2. Expected low infiltration rate of 1.27 L/s/m^2, at 75 Pa.
3. Expected high infiltration rate of 3.65 L/s/m^2, at 75 Pa.
4. Expected low ERV supply flow leakage rate of 3% of supply flow; *PassivHaus Institut*'s specified leakage rate
5. Expected high ERV supply flow leakage rate of 34% of supply flow
6. Expected 'conservative' temperature set points
7. Expected 'liberal' temperature set points
8. Economizer by-pass control option.

Parametric run 1 forms the baseline operating scenario under the typical conditions determined above, while runs 2 through 8 seek to explore the individual impact from the range of factors that were determined in Section 3. As with the validation analysis, sensible and latent heating and cooling recovery are analyzed in the parametric analysis. A snapshot of the heating sensible and latent recovery was obtained by considering a three day period during the heating season. Similarly, considering a three day period during the cooling season provides a snapshot of the cooling sensible and latent recovery. To normalize the impact of orientation, parametric runs are simulated in each of the four cardinal directions, and results averaged. The overall results from the eight parametric runs are summarized in Table 2 below and are discussed subsequently. Two sample results are presented in Figures 4 and 5 to highlight the evaluation process of the energy recovery.

Table 2 – Parametric analysis results summary

Parametric Run	Total Energy Use (GJ)	Annual Heating Energy (GJ)	Annual Cooling Energy (GJ)	Recovered Heating Energy (GJ)	Recovered Cooling Energy (GJ)
1	**25.43**	**7.15**	**3.11**	**9.27**	**0.100**
2	**25.21**	**6.91**	**3.14**	**9.29**	**0.100**
3	**29.40**	**11.51**	**2.74**	**8.97**	**0.100**
4	**25.71**	**7.43**	**3.08**	**10.47**	**0.112**
5	**25.04**	**6.79**	**3.16**	**7.76**	**0.081**
6	**24.10**	**5.95**	**2.97**	**9.32**	**0.036**
7	**28.52**	**9.42**	**3.56**	**9.64**	**0.151**
8	**25.26**	**7.15**	**2.99**	**8.89**	**0.100**

In Table 2, total energy use in GJ refers to the annual consumption of the suite, including all end uses. Annual heating and cooling energy in GJ represents the overall consumption of these end uses specifically, not including fan or pumping energy required. Recovered heating and recovery cooling energy in GJ represent the annual heating and cooling energy recovered through the modeled ERV device, respectively. The results of Table 2 were calculated by evaluating hourly variation, as exhibited in Figures 4 and 5 below, of the different energy levels form the *EnergyPlus* simulations.

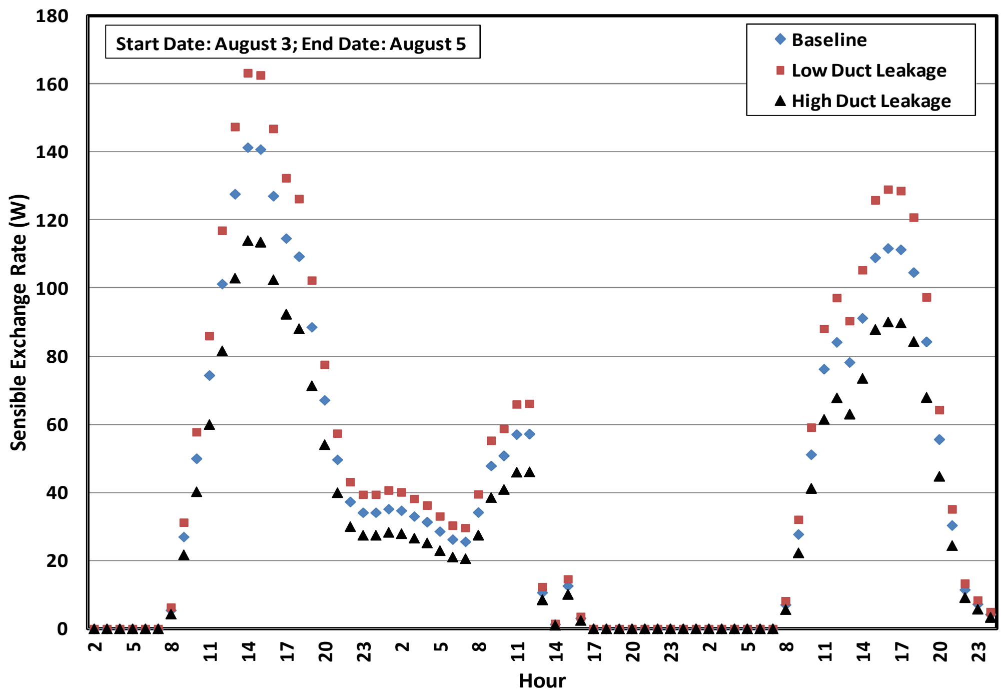

Figure 4 – Summer recovered sensible cooling as a function of leakage flow.

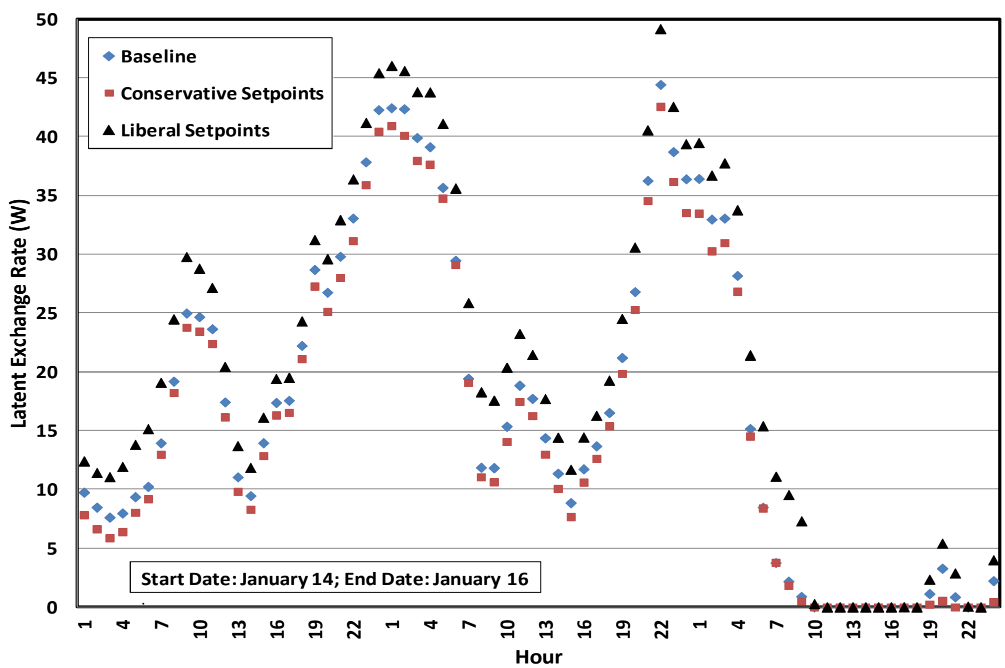

Figure 5 – Winter recovered latent heating as a function of indoor set point.

Infiltration Flow Impact

The impact of infiltration rates on ERV performance and annual suite heating and cooling consumption was the first parameter that was investigated. When compared to the baseline infiltration rate (Run #1 of Table 2), the low infiltration rate (Run #2 of Table 2) resulted in a reduction in annual heating energy, from 7.15 GJ to 6.91 GJ. A corresponding slight increase in annual heat recovered resulted, from 9.27 GJ to 9.29 GJ. The impacts to the ERV itself in terms of recovered heat are fairly insignificant. However, Run #3 with the high infiltration rate resulted in an increase in the annual heating consumption of the fan coil fairly significantly, to 11.51 GJ, while reducing the annual heat recovered from the ERV unit to 8.97 GJ.

Little impact to the sensible recovery rate in the winter was noted over the period studied, suggesting infiltration does not have a significant impact on sensible heat recovery during the winter. A more marked difference is seen when considering latent heat recovery. The hourly values of Run #3, showed a more pronounced reduction in latent recovery energy, at times when the latent recovery was peaking, when compared to the baseline. Impacts to ERV performance appeared to be a function of infiltration sensible and latent loads, as well as modified indoor temperature and humidity due to the infiltration flow encountered by the exhaust side of the ERV. In the case of sensible heating, the impact of temperature was reduced as any reduction in indoor temperature due to infiltration in the winter was remedied by the in-suite fancoil providing more heat, resulting in increased primary heating energy. However, there was no process to humidify or dehumidify the suite, and therefore, a more significant impact to the latent recovery of the ERV from infiltration was noted.

When analyzing summer conditions, lower modeled infiltration corresponded with a slight increase in annual cooling energy, from 3.11 GJ to 3.14 GJ, while annual recovered cooling energy through the ERV unit remained constant at 0.100 GJ. Modeled high infiltration conversely led to a decrease in annual cooling energy consumption, down to 2.74 GJ, while recovered cooling energy through the ERV unit remained constant at 0.100 GJ. The lack of a response to infiltration in the summer months was expected, as infiltration flows were reduced during the summer period as a function of indoor-outdoor temperature difference. Overall analysis of the infiltration parametrics indicated that expected infiltration rates in residential buildings were close to what can be considered as a best practice infiltration rate based on the more stringent air tightness standards currently available. Results corroborated the importance of a compartmentalization strategy in MURBs with regards to air tightness, and consequently, ERV performance.

ERV Leakage Flow Impact

Modeled ERV leakage flows represented leakage ratios through the ERV as a result of poor construction of the ERV unit itself. When considering ERV leakage, altering flow rates had direct impact on the ERV performance. The modeled low duct leakage flow rate resulted in a slight increase in annual heating energy consumption in the suite, from 7.15 GJ to 7.43 GJ. An increase in modeled annual heat recovered from the ERV, from 9.27 GJ to 10.47 GJ, was also observed. Conversely, the expected high duct leakage rate reduced annual heating consumption to 6.79 GJ, while also reducing annual ERV heat recovery down to 7.76 GJ. A much more direct impact to ERV performance was noted when compared to infiltration flows, as when supply mass flow rates through the ERV supply side were reduced, in the case of high ERV leakage, recovery rates are reduced as well at all time steps.

The low ERV leakage showed a slight increase in overall heating consumption compared to the baseline case. Conversely, the high ERV leakage rate resulted in lower heating energy consumption. ERV leakage was modeled directly as an imbalance to the ERV supply and exhaust flows, with a reduction in supply flow. Therefore, an overall increased amount of outdoor air entered the suite when ERV leakage was low, and more air made its way through the ERV core and into the suites.

When considering the summer condition, cooling energy recovery responded similarly to the heating recovery performance with respect to modifying ERV leakage. Total annual cooling energy recovery through the ERV increased from 0.100 GJ to 0.112 GJ when ERV leakage was low, and reduced to 0.081 GJ when ERV leakage was high. Response to ERV leakage was most pronounced during peak periods of recovery. Following the same logic as the heating recovery response, as leakage rates were increased in the ERV unit, the supply mass flow rate, and therefore recovery rate, was reduced.

Results showed that moving forward on improving the energy performance of MURBs partially relied on specifying ERV units with low leakage rates. As demonstrated, the leakage rates not only impacted energy performance, but also impacts indoor air quality concerns, as overall ventilation flows would be decreased. The energy modeling community in particular must be aware of correctly modeling leakage when comparing ERV models at the design stage, given the importance identified here.

Temperature Set point Impact

Indoor temperature set points were modeled as 24°C during the cooling season and 22°C in the heating season, with an 18°C overnight setback during overnight periods. The two other conditions analyzed represented a tenant attempting to be conservative in their energy use, with a 26°C cooling set point, and 21°C heating set point, and a tenant less concerned with energy use, with a 23°C set point year round. The results showed that the suite fancoil responds as expected during the heating season, as annual suite heating consumption decreases with more conservative set point, from 7.15 GJ to 5.95 GJ, and increases with more a more liberal set point, to 9.42 GJ. A fairly significant impact to total suite consumption was therefore demonstrated. Annual heat recovered through the ERV increased in both scenarios, to 9.32 GJ and 9.64 GJ with conservative and liberal set points, respectively, compared to a baseline of 9.27 GJ.

An increase in winter recovery rate was seen with liberal (i.e. warmer in winter) set points. Increased recovery was a function of the increased temperature differential between the indoors and outdoors during peak periods. Contrary to the infiltration and ERV leakage cases, the liberal set point did not equate to a more optimal system as much more heating consumption was needed. Total heating consumption was close to double that of the heating energy required to maintain the more conservative set point.

A more conservative temperature set point (i.e. colder in winter) led to an expected reduction in annual heating energy consumption, however also led to an increase in annual recovered heat when compared to the baseline. A reduction in heat recovery was expected given a smaller indoor outdoor temperature differential. Therefore, to account for the increase in recovered heat, the summertime heating energy recovery was analyzed. The conservative cooling set point was set higher in the cooling season, to 26°C, which led to more hours throughout the cooling season where the outdoor temperature was lower than the indoor temperature. In this situation the ERV acts to heat the incoming air stream. Analysis showed that ERV response generally occurs overnight where outdoor temperatures drop. The overnight response would also feasibly occur throughout the shoulder season, where outdoor temperatures would be milder.

The impact of temperature set point on cooling recovery was also analyzed. The conservative temperature set point led to a decrease in annual suite cooling energy consumption, from 3.11 GJ to 2.97 GJ, while the liberal set point increased annual cooling consumption to 3.56 GJ. The same intuitive relationship demonstrated in the response to heating consumption was observed. The response of the ERV to temperature set point was relatively more significant regarding the cooling energy recovered. Annual recovered cooling through the ERV decreased from 0.100 GJ to 0.036 GJ with conservative temperature set points and increased to 0.151 GJ with liberal set points. Sensible and latent recovery rates again appeared to respond fairly similarly in comparison to one another. Analysis indicated that more conservative temperature set points led to reduced recovery rates during all time steps, due to a reduced temperature differential. Annual recovery rates through the ERV were conversely increased when set points were more liberal. Therefore the inverse of the unwanted heating effect produced when examining heating energy recovery was not seen, or was much less pronounced, when considering cooling recovery. Considering the Toronto climate, it is much less likely that the outdoor air temperature will increase during the heating season so much so that the ERV would respond by cooling the incoming air rather than heating it.

ERV Control Strategy Impact

The analysis of indoor temperature set points highlighted the fact that unwanted heating of the incoming air can occur during the cooling season. Overheating can also occur overnight during the cooling season, as well as throughout the shoulder season, where outdoor temperatures fluctuate around the indoor temperature set point. The overheating impact would be undesirable and can counteract the fancoil unit setting. An air side economizer mode for the in suite ERV was explored as a method of circumventing the ERV core when outdoor temperatures were favourable. The baseline operation, by comparison, was operated at a constant flow rate through the ERV unit.

The economizer by-pass simulation resulted in no change to overall annual heating consumption, remaining at 7.15 GJ, while reducing annual heat recovered through the ERV slightly from 9.27 GJ down to 8.89 GJ. Annual suite cooling energy consumption was slightly reduced to 2.99 GJ from 3.11 GJ, while annual cooling recovered through the ERV was unchanged at 0.100 GJ.

The lack of change to heating energy consumption was a function of the economizer operation, which only operates to provide a free cooling effect. The resultant decrease in recovered heating energy therefore must represent the decrease in the overheating effect of the ERV during the shoulder season and summer time. An analysis of heating energy recovery in late June, where mild outdoor temperatures may be expected, showed that in the baseline, uncontrolled option more heating energy was recovered when compared to the economizer option. In comparison, ‘gaps’ in the economizer heating recovery indicated periods of time when the outdoor conditions were within a favourable range for cooling, yet below the indoor temperature set point. Therefore while only a small impact to heating consumption was seen, an economizer can work to reduce overall cooling energy consumed, as well as avoid unwanted heat recovery, resulting in a system working optimally.

The economizer control strategy analyzed was fairly simple, however is often not used with small scale in-suite ERVs due to restrictions from space constraints for mechanical equipment. Alternatively, a control strategy would be to use operable windows, which can be automated to open and close in response to outdoor temperatures, in conjunction with the ERV unit shutting down. Window automation would provide free cooing, reacting to the outdoor and indoor temperatures, and eliminate the need for by-pass ductwork within the ERV. An added benefit of this strategy was the reduction of fan run time, leading to additional energy savings not captured in the parametric analysis.

Such a control strategy is however theoretical at this point, and many considerations would need to be taken into account, such as maintaining individual occupant controllability. Alternatively, property managers may focus on educating tenants regarding proper operation of their ERV, including its use in response to manual operable window adjustment. Education could highlight that to optimize operation; ERV units should ideally be turned off whenever windows are left open, and turned back on when they are closed, to maintain ventilation rates while avoiding unwanted recovery. An educational strategy is less likely to result in optimal performance; however is a more realistic option in the short term. Education can also be relied on in existing buildings with ERV units already installed.

6 Conclusions

ERV units are currently implemented to achieve savings in heating and cooling consumption in newer, high performance multi-unit residential buildings. The performance of ERV units under realistic operating conditions was evaluated, by conducting a simulation study using *EnergyPlus*. The simulation model was first validated by comparing the results of simulation with actual field measurements. The impacts of several parameters to in-suite ERV performance in high rise residential buildings in Toronto were analyzed and discussed. The parameters considered were: the infiltration rates, ERV leakage rates, temperature set points, and ERV controller operation. The simulation results showed that:

- Typical air sealing practices were close to optimal in terms of ERV performance when infiltration was considered. The typical infiltration flows were close to the expected optimal flows due to in-suite compartmentalization and the associated weather-stripping and air sealing required. As a result, infiltration rates were found to have insignificant impact of ERV performance in this context.
- Leakage rates within the ERV had a more direct impact on ERV recovery rates, and hence should be considered in conjunction with nominal ERV effectiveness. Leakage of supply flows can also result in indoor air quality problems, as less ventilation air makes it to the space. Hence, proper construction and installation of ERV units were seen to be of primary concern. One possible solution was seen to be the application of *PassivHaus Institut*'s specified leakage rate as a standard. Energy modellers should pay attention to leakage flows in additional to ERV effectiveness, to accurately model ERV unit performance.
- Modification of temperature set points showed a bigger impact on primary heating and cooling consumption, with less impact on recovery rates. Improper use was exemplified by considering heating recovery while conservative temperature set points are used, leading to excess heating in the summer and shoulder seasons.
- Economizer operation resulted in reduced annual cooling energy consumption as well as reduced annual heating energy recovery, attributed to the elimination of some of the unwanted summertime heat recovery. The practical application of an economizer bypass in small ERVs was seen to be a potential limiting factor, and therefore alternative strategies need to be investigated.

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