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The IVAIRE Study: Relative Performance of Energy and Heat Recovery Ventilators in Cold Climates

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Abstract**—**This paper describes the results obtained in a two-year randomized intervention field study investigating the impact of ventilation rates on indoor air quality (IAQ) and the respiratory health of asthmatic children in Québec City, Canada. The focus of this article is on the comparative effectiveness of heat recovery ventilators (HRVs) and energy recovery ventilators (ERVs) at increasing ventilation rates, improving IAQ, and maintaining an acceptable indoor relative humidity (RH). In 14% of the homes, the RH was found to be too low in winter. Providing more cold and dry outside air to under-ventilated homes in winter further reduces indoor RH. Thus, low-RH homes in the intervention group were chosen to receive ERVs (instead of HRVs) to increase the ventilation rate. The installation of HRVs or ERVs led to a near doubling of the ventilation rates in the intervention group homes which led to a significant reduction in the concentration of several key of pollutants. The ERVs were also effective in maintaining an acceptable indoor RH since they avoided excessive dehumidification of the home by recovering moisture from the exhaust airstream through the enthalpy core, otherwise associated with increased cold supply air rates.

Keywords**—**Asthma, field study, indoor air quality, ventilation.

I. INTRODUCTION

THE objectives of this study were to determine whether ventilation interventions will lead to an increased ventilation rate in under-ventilated homes, to a decrease in indoor air contaminants, and to a corresponding decrease in the frequency of asthma symptoms in asthmatic children. The first phase of the field study involved 111 homes where three residential home visits were conducted (two during the heating- season (October to April) and one in summer (May to September)) where a number of IAQ-relevant chemical, biological and physical parameters were measured over a 6- to 8-day period. A series of questionnaires capturing information related to housing characteristics and occupant behavior were also administered during the home visits. In the second phase, any home with one air exchange rate (AER) measurement below 0.25 h^{-1} or two below 0.30 h^{-1} was considered eligible for the intervention. Of the 111 homes involved in the study, 83 were eligible for the intervention, and these were randomly divided into two groups. One group of participants (n=43) had their ventilation rates increased by a combination of: installation of a HRV, ERV, and/or modification of the existing ventilation system. The other group did not have any modifications done to the ventilation rate and served as a control group (n=40). The monitoring in the second phase after the intervention was identical to the first phase and was used to assess the effectiveness of the intervention on improving the IAQ and the respiratory health. This paper focuses on the comparative effectiveness of the HRV and ERV at increasing ventilation rates and improving IAQ.

II. EXPERIMENTAL

The AERs measured in the child's bedroom and in the living room over a 6-8 day period using the perfluorocarbon tracer (PFT) technique developed by the Tracer Technology Group at Brookhaven National Laboratory [1]. An analysis of triplicate capillary adsorption tube samplers (CATS), placed side by side, showed a standard deviation of less than 6% in the measured AER. The AER was also measured over a 4-5 hour period in the child's bedroom using sulfur hexafluoride (SF_6) tracer gas decay according to the ASTM test method E 741-00 [2] using an Innova 1312 or 1412 photoacoustic field gas monitor. RH and temperature were measured with an Onset HOBO U12-013 data logger, and the CO_2 concentration was measured with a Vaisala GMW21 CO_2 sensor. Additional information about the other chemical, biological, and physical parameters measured in this study is detailed in Lajoie et al. [3].

The interventions consisted of the installation of either an HRV or ERV and education of the home owner on its use and maintenance. Houses with existing HRVs had the installation and/or controls modified to produce higher air exchange rates. ERVs, which can transfer moisture through their enthalpy core to transfer not only sensible heat but also latent heat (moisture) into the incoming outdoor air stream, were installed in the homes which had indoor RH lower than 35%. Homes which had other factors present, such as low heating-season indoor temperature, low number of occupants and presence of mechanical ventilation, which could contribute to low indoor humidity levels during the heating-season also had an ERV installed. Overall, the intervention group had 18 ERVs and 25 HRV's installed. Generally, HRVs or ERVs were installed in the basement or, in a few cases, in the attics. Supply and return ducts were added on each occupied floor of the house, and when it was practical to do so a supply air outlet was placed in the child's bedroom. The overall objective was to provide an increase in ventilation to the whole house rather than just the child's bedroom.

Prior to conducting the individual ventilation intervention, the precise prescription was modeled for several homes

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computationally and physically in the National Research Council's Indoor Air Research Laboratory (IARL). The computational fluid dynamics (CFD) calculations were performed using FLUENT® and were conducted to optimize the geometry and initial placement of any supply and return air vents in the child's bedroom that would be required during the installation of an HRV or ERV. The results of the computational models were then validated physically in a 1:1 scale model of the child's bedroom in the IARL.

In order to assess the potential for harmful pollutants to cross through the heat-transfer membrane of the ERV's that were used in this study, we conducted an analysis of the relative change in concentration for different VOCs relative to the indoor RH. Compounds with similar physical-chemical properties to water would be expected to interact with the heat-transfer membrane in a similar way and exhibit similar concentration profiles. An inter-comparison of the relative concentration profiles in both ERV and HRV sub-groups before and after the intervention could provide some insight into the potential for these VOC's to cross the heat-transfer membrane along with water. To conduct this analysis, we chose to use formaldehyde and toluene. These two different compounds were selected because they were routinely measured in indoor air, they have different source types, and are both volatile yet have different physical-chemical properties.

III. RESULTS AND DISCUSSION

From Fig. 1, it can be seen that the majority of the homes were under-ventilated prior to the intervention with 78% of the homes not attaining our nominal ventilation goal of 0.30 h^{-1} for the pre-intervention heating-season.

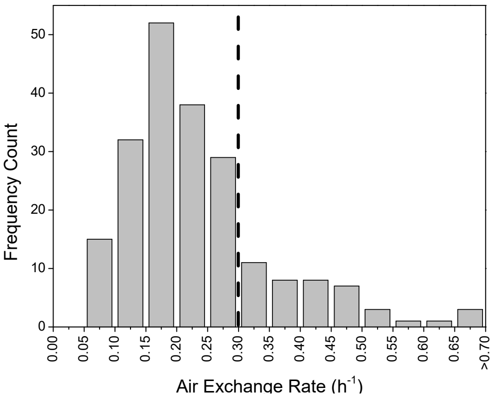

Fig. 1 Histogram of the AERs (h^{-1}) measured in the child's bedroom (n=111) for the first two pre-intervention winter visits (dashed vertical line indicates our nominal ventilation goal of 0.30 h^{-1})

Prior to conducting the ventilation interventions 14% of the homes had RH levels that were either below or on the low end of Health Canada's recommended value for winter of 30-55% [4]. These homes were at risk of excessive dehumidification during the heating-season following the intervention because increasing the ventilation rates in these homes would introduce dry outside air which would further depress the indoor RH.

Table I shows the pre- and post-intervention change in the AER's. The ventilation rates for either of the ERV or HRV sub-groups were adjusted to provide an additional 0.15 h^{-1} of ventilation irrespective of the pre-intervention ventilation rate. Median values are presented here as this dataset is not normally distributed which is generally the case for most environmental measures. Following the intervention, the median AER measured in the child's bedroom during the heating-season increased from 0.17 h^{-1} to 0.36 h^{-1} in the intervention group, whereas there was no statistically significant change in the control group.

TABLE I
MEDIAN PRE- AND POST-INTERVENTION AER'S MEASURED IN THE BEDROOM FOR THE CONTROL AND INTERVENTION GROUP

Season	*Cohort*	*Pre (h^{-1})*	*Post (h^{-1})*	Δh^{-1} (%)
Winter	Control (n=39)	0.18	0.21	+0.03 (+17)
	Intervention (n=43)	**0.17**	**0.36**	**+0.19 (+111)**
	ERV (n=18)	**0.25**	**0.43**	**+0.18 (+72)**
	HRV (n=25)	**0.17**	**0.33**	**+0.16 (+94)**
Summer	Control (n=39)	0.42	0.48	+0.06 (+14)
	Intervention (n=43)	**0.32**	**0.64**	**+0.32 (+100)**
	ERV (n=18)	**0.30**	**0.57**	**+0.27 (+90)**
	HRV (n=25)	**0.21**	**0.81**	**+0.61 (+285)**

Note: **Bold** indicates a statistically significant change from the pre- and post-intervention phase as determined from a Wilcoxon signed rank test (p=0.05).

From Table I and Fig. 2, it can be seen that the targeted increase of 0.15 h^{-1} was achieved in the majority of the homes with only two outliers (one being a non-compliant participant turning off their HRV and the other resulting from a faulty unit control). The HRV and ERV sub-groups experienced a median increase in AER of 0.16 h^{-1} and 0.18 h^{-1}, respectively. It should be noted that the homes receiving an HRV had consistently lower summer and winter ventilation rates during the pre-intervention phase compared to the homes receiving an HRV (*winter*: 0.25 h^{-1} (ERV) vs. 0.17 h^{-1} (HRV); *summer*: 0.30 h^{-1} (ERV) vs. 0.21 h^{-1} (HRV)). Fig. 2 shows the individual changes in the ventilation rates following the intervention for both the ERV and HRV sub-groups.

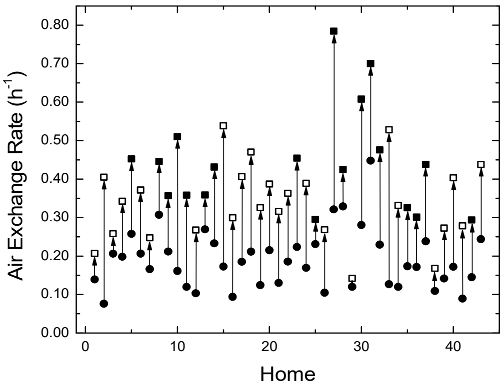

Fig. 2 Pre-intervention (●) and post-intervention HRV (□, n=25) and ERV (■, n=18) winter AER's measured in the child's bedroom

The ERVs and HRVs were equally effective at increasing the AER's within the intervention cohort and at allowing the homes to achieve our post-intervention ventilation rate goal of 0.30 h^{-1}.

A comprehensive description of the pre- and post-intervention changes in the chemical, physical, and biological IAQ parameters is reported in Lajoie et al. [3]. Briefly, a statistically significant reduction in concentration, of up to 55%, was observed in most VOC's in the intervention group relative to the control group [3]. Table II gives an overview of some selected IAQ relevant parameters.

TABLE II
MEDIAN CONCENTRATIONS OF SELECTED IAQ RELEVANT PARAMETERS MEASURED DURING THE PRE AND POST INTERVENTION VISITS DURING WINTER

Parameter	*Cohort*	*Pre-Intervention*	*Post-Intervention*	Δ (%)
CO_2	Control	1020	1027	+7 (+1)
(24-hr, ppm)	Intervention	899	770	**-199 (-22)**
Formaldehyde	Control	35.9	36.0	0
(μg m^{-3})	Intervention	34.3	24.1	**-10.2 (-30)**
Toluene	Control	15.7	11.2	-4.5 (-29)
(μg m^{-3})	Intervention	17.5	6.5	**-11 (-63)**
Airborne Mold	Control	69	55	-14 (-20)
Spores (CFU m^{-3})	Intervention	57	35	**-22 (-68)**
Ethyl acetate	Control	7.8	7.6	-0.2 (-3)
(μg m^{-3})	Intervention	10.9	5.5	**-5.4 (-49)**
α-pinene	Control	10.6	8.3	-2.3 (-22)
(μg m^{-3})	Intervention	13.3	5.9	**-7.4 (-55)**

Note: **Bold** indicates a statistically significant change from the pre- and post-intervention phase as determined from a Wilcoxon signed rank test (p=0.05).

For a few VOCs, there was no statistically significant reduction in concentration in the intervention group before and after the intervention. Significant reductions in airborne mold spores were also observed following the intervention. No statistically significant reduction in the concentration of $PM_{2.5}$ or PM_{10} was observed. This may be due to the sampling protocol for PM which was monitored during the first 4-5 hours of the visit during the heating-season and that the fact that PM levels were easily influenced by occupant behavior such as cooking.

Table III shows the pre- and post-intervention change in the temperature and RH measured in the home for the cohorts receiving the HRV or ERV. It should be noted that the temperature and RH were measured in the living room only during the summer visits and that the mean values are presented here because both datasets are normally distributed datasets.

From Table III, it can be seen that following the intervention both the ERV and HRV sub-groups experienced reductions in temperature, ostensibly from the addition of colder partially tempered outside air into the home; however, the reduction was only statistically significant in the child's bedroom. This is likely due to the fact that the child's bedroom generally had a fresh air supply duct installed in it and being smaller than the living room it would be more readily cooled down by additional partially tempered air.

During winter, the homes receiving the HRV's had mean *reductions* in RH of -4.7% and -11.4% in the child's bedroom and living room respectively. This was expected as we increased the supply of dry outside air into the homes without providing additional humidification. The homes receiving ERV's had mean increases in RH of +3.6% and +0.1% (not statistically significant) in the child's bedroom and living room respectively. The fact that there was no statistically significant change in RH for the homes receiving an ERV indicates that the units effectively buffered the winter RH in the homes allowing us to increase the ventilation rates without excessively drying out the homes.

TABLE III
MEAN RH AND AIR TEMPERATURE MEASURED FOR THE PRE- AND POST- INTERVENTION PHASES

Parameter	*Location*	*Ventilator*	*Winter*		*Summer*	
			Pre	*Post*	*Pre*	*Post*
Temperature (ºC)	Cbr	HRV	18.3	.9	-	-
	LR	HRV	21.3	21.0	22.9	23.6
	Cbr	ERV	17.6	16.8	-	-
	LR	ERV	21.9	21.7	22.8	23.1
RH (%)	Cbr	HRV	**50.0**	16 **45.2**	-	-
	LR	HRV	**45.3**	**33.9**	**49.0**	**58.1**
	Cbr	*ERV*	42.9	46.5	-	-
	LR	*ERV*	35.8	35.9	**46.1**	**58.5**

Note: **Bold** indicates a statistically significant change in the pre- and post-intervention measurement as determined from a paired t-test (α=0.05). Location: Cbr = child's bedroom, LR = living room.

During summer, both sub-groups experienced an increase in RH in the living room following the ventilation intervention (NB: the RH is was only measured in the living room in summer). There was a statistically significant increase in RH of +9.1% for the HRV sub-group and +12.4 % RH for the ERV sub-group. The perceived lack of any RH "buffering" in the ERV sub-group in summer could be due to the indoor and outdoor RHs being similar as a result of increased natural ventilation. In a previous publication, Won et al. showed that the increased use of natural ventilation by our study participants, by opening doors and windows, was associated with a statistically significantly (p<0.001) higher AER in the home [5]. The increased use of natural ventilation in summer would have allowed large amounts of moist outside air into the home by bypassing the ERV which would serve to equalize the indoor and outdoor RHs. With little or no RH gradient present, there would be no thermodynamic driving force encouraging the moisture to cross the heat-transfer membrane. Finally, the very large increase in the summertime ventilation rates observed for both sub-groups, 90% and 283% increase in the AER's for the ERV and HRV sub-groups respectively, should have normalized the indoor RH between both groups which is what was observed (58.5% RH (HRV) vs. 58.1% RH (ERV) for the post-intervention summer visit).

Zhang et al. have proposed that ERVs, by virtue of their semi-permeable heat transfer membranes, may possibly transfer hydrophilic gases, such as formaldehyde, and contaminate the incoming (fresh) air stream [6]. This would be problematic as the same desirable feature, which is of having a semi-permeable membrane to water vapour, could also entrain the transfer of harmful pollutants, such as formaldehyde, into the supply air. In this case, gases with similar physical-chemical properties, such as polarity, to those of water would also be expected to be transferred across the heat-transfer membrane of the ERV along with water. One way to confirm if the membrane is systematically transferring other compounds beyond water vapour and air is to compare the relative change in the concentration of different VOC's relative to the RH. If a VOC exhibits similar concentration patterns to those of RH before and after the intervention then it may be that the VOC is crossing through the membrane along with the water vapour.

In this paper, we also intended to address the concern of the cross-contamination of formaldehyde as its chemical properties are similar to that of water. Table IV below provides a comparison of selected physical-chemical properties for water, formaldehyde and toluene that would be relevant in defining the diffusivity of a particular gas through a permeable heat transfer membrane.

TABLE IV
CHEMICAL PROPERTIES OF WATER, FORMALDEHYDE, AND TOLUENE [8]

Parameter	*Water*	*Formaldehyde*	*Toluene*
Molecular Weight (g/mol)	18.0	30.0	94.2
Boiling Point (°C)	99.9	-19.5	110.6
Vapor Pressure (kPa @ 25 °C)	3.1	<0.2	3.8
Water Solubility (g/L @ 25 °C)	miscible	miscible	0.52
$\mathrm{LogK_{ow}}$	NA	0.35	2.73
Dipole Moment (debye, [7])	1.85	1.85	0.36

Table V shows the relative changes in RH, formaldehyde, and toluene before and after the ventilation intervention for the ERV and HRV sub-groups.

From Table V, it can be seen that the relative changes in concentrations for RH, formaldehyde, and toluene are different. For toluene, we see similar absolute and percent reductions during summer and winter after the intervention for both the ERV and HRV sub-groups. The case is similar for the RH measured in both the ERV and HRV sub-groups in winter while in the summertime both groups experienced increases in RH. The relative changes in the formaldehyde concentrations differed from those for RH and toluene. Notably, there were significant differences between the pre-intervention wintertime formaldehyde concentrations for the ERV and HRV sub-groups (43.8 μg m^{-3} vs. 30.1 μg m^{-3}). For the current study, Aubin et al. observed a significant inverse exponential relationship between a home's AER and the indoor concentration of formaldehyde as shown Fig. 2 [9].

TABLE V
PRE AND POST INTERVENTION MEAN RH AND MEDIAN FORMALDEHYDE AND TOLUENE CONCENTRATIONS IN THE ERV AND HRV SUB-GROUPS

Ventilator	Winter (Cbr)		Δ	Summer (LR)		Δ (%)
	Pre	Post		Pre	Post	
Water (RH, %)						
HRV (n=25)	50.0	45.2	**-4.7** **(-9.5%)**	49.0	58.1	**+9.1** (+18.5)
ERV (n=18)	42.9	46.5	+3.6 (+7.9%)	46.1	58.5	**+12.4** (+26.8)
Formaldehyde (μg m^{-3})						
HRV (n=25)	43.8	24.5	**-18.6** **(-42%)**	57.2	45.3	**-11.9** **(-21%)**
ERV (n=18)	30.1	28.1	**-2.0** (-7%)	61.3	55.7	**-5.6** (-9%)
Toluene (μg m^{-3})						
HRV (n=25)	10.7	7.1	**-3.6** **(-33%)**	14.0	7.6	**-6.4** **(-46%)**
ERV (n=18)	11.1	8.4	**-2.7** **(-24%)**	15.9	8.1	**-7.8** **(-49%)**

Note: **Bold** indicates a statistically significant change from the pre- and post-intervention phase from a Wilcoxon signed rank test (*p*=0.05).

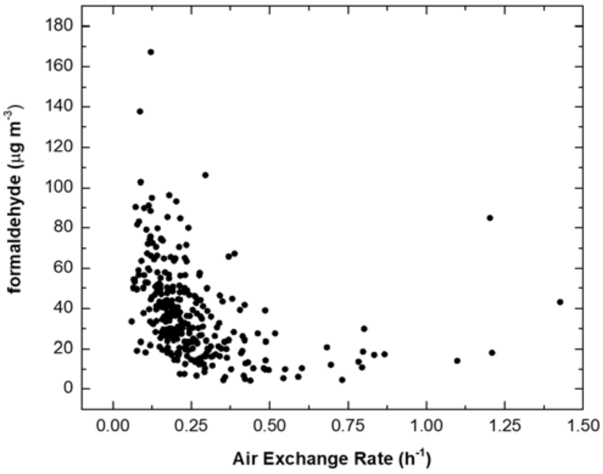

Fig. 3 Winter season formaldehyde measured in the child's bedroom for all homes during the pre-intervention phase (n=111) and for all homes in the control group (n = 40) during the post-intervention phase

Therefore, all things being equal, a home with a lower AER would be expected to have higher formaldehyde concentrations. Then, for a given increase in AER, the corresponding decrease in formaldehyde will depend on what the initial pre-intervention AER was. From Fig. 3, it can be seen that the lower the initial AER the higher the corresponding decrease in formaldehyde for a given increase in AER. This is what we observed in this case as the HRV sub-group had a lower pre-intervention wintertime AER relative to the ERV sub-group (0.17 h^{-1} vs. 0.25 h^{-1}) and both groups had similar increases in their post-intervention wintertime AER (0.18 h^{-1} vs. 0.16 h^{-1}) yet the HRV sub-group experienced a much larger reduction in formaldehyde than the ERV sub-group (18.6 μg m^{-3} vs. 2.0 μg m^{-3}). The HRV sub-group may have experienced a larger reduction in formaldehyde simply because the initial concentrations were higher and the AERs are lower to begin with.

IV. CONCLUSION

This study demonstrates that under-ventilated homes can be corrected through a careful retrofit with HRV and ERV systems. Both ERVs and HRVs were shown to be equally effective at increasing the air exchange rates in the participating homes. ERVs were shown to be useful alternatives for providing an acceptable indoor RH in cold climates because they can provide additional outside air for ventilation while minimizing reductions in indoor RH during winter.

We observed no direct evidence supporting the presence of cross-contamination of formaldehyde across the exhaust and incoming air streams in the ERVs. Since the RH, formaldehyde, and toluene concentrations exhibited very different concentration profiles between the pre- and post-intervention phases we cannot conclusively state that they are behaving similarly within the same indoor environment. The smaller observed reduction in formaldehyde concentrations with the ERVs compared to the HRs may be due to it transferring across the enthalpy core, or due to its lower initial wintertime concentration, or to the overall lower winter RH within the ERVs sub-group since lower RHs promote less off-gassing of formaldehyde [10]. If the re-entrainment of formaldehyde across the ERV enthalpy core was in fact occurring, it might have been obscured by the fact that the ERV was able to provide sufficient ventilation to dilute and reduce the indoor concentration of formaldehyde in the end.

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