Residential balanced ventilation and its tested impacts on indoor pressure and air quality

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ABSTRACT

This paper presents results from a project on the assessment of the indoor air quality (IAQ) benefits that might accrue from the use of a balanced energy recovery ventilation system. The study compared the whole-building pressure, IAQ and ventilation performance of a balanced energy recovery ventilation (ERV) system with that of an exhaust-only ventilation system (continuous exhaust from master bathroom). This investigation compared experimentally the impacts of the two ventilation systems in a side-by-side testing configurations using the Canadian Centre for Housing Technology's (CCHT) twin houses to demonstrate and quantify the potential indoor air quality benefits of balanced ventilation system. The testing approach was a combination of building air leakage and HVAC characterization, envelope differential pressure, perfluorocarbon (PFT) tracer gas tests, sampling of aldehyde and volatile organic compound (VOCs). Two VOCs, toluene and α-pinene, were dosed at a constant rate to mimic indoor sources. The winter testing results have shown that a house operated with an ERV was under low positive pressure (1 to 3 Pa) and the house operated with an exhaust-only system was under negative pressure (-1 to -3 Pa). The effect of positive pressure on the IAQ has shown that relevant IAQ pollutants were significantly reduced in the house operated with a balanced ERV system. Average concentrations of formaldehyde in houses with balanced ventilation were reduced by 10-66% over houses operated with exhaust system. The average concentrations of two VOCs added (aPin and dTol) were respectively significantly reduced by 8-89% and 14-76% with partial mixing and with no mixing, respectively. The house with balanced ERV system had an average weekly space heating and ventilation total energy consumption reduced by 3.9-8.5%. The balanced (ERV) ventilation system was an energy-efficient solution to improve IAQ by generating a positive indoor pressure (1-3 Pa).

KEYWORDS

Ventilation, ERV, Exhaust-only, Positive pressure, IAQ

1 INTRODUCTION

Ventilation energy consumption is a significant part of the energy consumption and cost of homes. The energy efficiency of residential buildings has steadily increased since 1970's due to improvements in construction methods (air-sealed building enclosures) and HVAC technology (Wray 2000). A major component of this improvement in energy efficiency has come as a result of reduced uncontrolled air leakage through the building envelope. Over the same period, changes in building materials, appliances, home furnishings and manufactured products have resulted in new types of indoor pollutants and increased emissions levels (Sherman 2007). These indoor pollutants can include moisture generated indoor (people, plants and activities such as cooking and showering), contaminants and odours generated by interior sources (people, cooking, household cleaners, and off-gassing of interior finishes and furnishings), and contaminants from exterior air (dust, particulates, allergens, and mould). While source control is an essential first step toward limiting exposure to indoor pollutants, adequate ventilation (paired with infiltration) is a critical means of establishing and maintaining indoor air quality. In order to provide a healthy indoor environment for building occupants, most jurisdictions prescribe residential ventilation rates based on the size of the liveable space and the number of anticipated occupants. Builders have traditionally met the requirements with central exhaust-only systems, which are relatively simple to install and have low initial cost (Wray 2000). As interest in energy conservation grows, balanced supply and exhaust systems are becoming increasingly popular in cold climates because they allow for heat to be recaptured from warm exhaust air. Balanced ventilation systems also allow for pre-filtration of supply air and prevent depressurization of homes, which can have negative effects on indoor air quality (Russel 2005). There is a lack of research to support allowing credit for better performing residential mechanical ventilation systems, such as balanced ventilation compared to exhaust-only ventilation. Building codes and ventilation standards do not attempt to address delivery of outdoor air to each space or forced air circulation/distribution of ventilation air. Instead, an assumption is made that for all ventilation system situations, the entire house is a single, well-mixed zone and the focus is only on relative annual average exposure of contaminants. With this assumption as the basis for ventilation design, the ventilation rate must be high enough to accommodate the worst performing system, which is exhaust-only ventilation.

Rudd (Rudd 2000) conducted a study on the in-situ impacts of various ventilation systems using two nearly identical (one with vented attic, the other with an unvented attic) unoccupied, single-family, detached lab homes. The project included five tests; Baseline (no ventilation), Exhaust (from master bathroom), Exhaust with mixing (exhaust from master bathroom and 20% central fan operation), CFIS (central-fan-integrated supply ventilation and 33% central fan duty cycle) and ERV (balanced ventilation with no central fan operation). Exhaust ventilation testing showed lower uniformity of outdoor air exchange rate between living space zones, and higher concentrations of particulates, formaldehyde and other Top 20 VOCs than did the supply and balanced ventilation systems. In contrast, the supply and balanced ventilation systems showed that there is a significant benefit to drawing outside air from a known outside location, and filtering and fully distributing that air. Total Volatile Compound (TVOC) data showed that, compared to the Exhaust system, the CFIS and ERV ventilation systems reduced TVOC by 47% and 57% respectively, averaged between the two houses. Compared to the Baseline test, the Exhaust system increased TVOC by 37% in House 1 main zone, and increased TVOC by 18% in the House 2 master zone. Vornanen-Winqvist (Vornanen 2017) conducted a case study of ventilation and IAQ investigations in a renovated school in Finland. The ventilation system was shown to be crucially unbalanced with fluctuation of large negative and positive pressures. To eliminate potential harmful effects of the building related sources and infiltration airflows, the AHU was adjusted to generate a 5-7 Pa positive indoor pressure for 4 months. Results showed a significant decrease of indoor TVOC concentration and indicated that the possible impurities infiltrated by the large negative pressure were potential causes for the complaints from building's occupants.

The objectives of this study were to investigate the IAQ-related benefits that might accrue from the use of a balanced (HRV or ERV) ventilation system and to demonstrate and quantify the effect of a neutral or positive indoor pressure which would limit infiltration from unknown adjacent zones and decrease the concentration of indoor contaminants. The study was performed through heating season period (2016/17) for baseline testing and testing with partial mixing and without mixing and a cooling season period (summer of 2017) for testing with continuous mixing, in the same twin houses. However, this paper presents only some results from the heating season testing periods of winter 2016/17.

2 EXPERIMENTAL METHOD

A rigorous side-by-side testing methodology was used to compare the whole-building, multi-zone, indoor air quality performance of continuous exhaust ventilation from master bathroom and energy recovery ventilation as a main exhaust from kitchen and bathrooms and supply to the return air plenum of the Furnace. The baseline side-by-side test (Test 1) was undertaken over one week in October 2016 with no central fan operation (furnace fan off and no heating/cooling) and all intakes and exhaust hoods/vents sealed externally. The side-by-side test (Test 2 and 3) were undertaken over two weeks in January 2017 with partial mixing (20% central fan operation) and in a heating mode with thermostat set at 22°C in both houses. The side-by-side tests (Test 4 and 5) were undertaken over two week in January and February 2017 without mixing, thermostats set on "Auto" and heating mode at 22°C in both houses.

2.1 CCHT Houses

The Canadian Centre for Housing Technology (CCHT) features twin research houses to evaluate the whole-house performance of new technologies in side-by-side testing. Figure 1 shows the reference and the test houses. The twin houses are a typical 2–storey wood-frame house, with 210 m^2 liveable area, built to the R-2000 standard. Features of the house include: a cast-in-place concrete basement, standard 2' x 6' wood frame wall construction, a high efficiency sealed combustion condensing gas furnace, a power vented conventional hot water heater, and an energy recovery ventilator. A single centrally located programmable thermostat controls both the space heating and cooling systems. At time of construction, the house had an air tightness characteristic of 1.5 ach @ 50 Pa – 30% below the R-2000 requirement.

Figure 1 – CCHT Facility – House 1 (M24-B on the right) and House 2 (M24-C on the left)

An important and unique feature of the twin house facility is the simulated occupancy system, with over 60 on/off events per day. The system is based on home automation technology and simulates the activities of a family of two adults and two children. Simulated events include: the operation of major appliances (dish washer, stove, washer & drier), lights, and water draws (shower, bath, kitchen sink). Incandescent bulbs are used to simulate heat gains from humans (60 W per adult, 40 W per child) at various locations in the house. The CCHT research houses are equipped with a data acquisition system (DAS) consisting of over 250 sensors and 23 meters (gas, water and electrical), reading the sensors every 5 minutes and provides hourly averages. Meter data are recorded on a 5 minute-basis. The DAS captures a clear history of the house performance in terms of temperature, humidity and energy consumption. A complete set of weather data is also available from a nearby weather station.

2.2 Side-by-side Testing

The CCHT houses are identical with ERV's operating in both houses. The houses were modified by incorporating an exhaust fan installed in the master bathroom of both houses. The existing ERVs are installed as partially dedicated systems with direct connection of ERV supply air stream to the air handler air return plenum and stale air exhausted from kitchen and bathrooms. A series of experiments were performed to obtain data for different residential ventilation systems, one balanced ventilation using an ERV and exhaust-only ventilation, either with or without mixing. Experiments were also performed to obtain data for the two houses without mechanical ventilation as baseline comparison of the ventilation systems. Four side-by-side comparisons have been evaluated; _Baseline Test_ conducted to benchmark all measured parameter with no ventilation and space conditioning systems operating, and where all intake and exhaust vents were sealed externally, _Mechanical Ventilation Test with Partial Mixing_ conducted with central air distribution mixing system, with central system fan cycle of 48 minutes OFF and 12 minutes ON, and _Mechanical Ventilation Test without Mixing_ conducted without central air distribution mixing system (furnace fan OFF). Furnace fan goes ON only when there is call for heating.

Table 1: Side-by-side experimental design

Test #	Type	House 1 (M24-B)	House 2 (M24-C)
1	Baseline	No mechanical ventilation	No mechanical ventilation
2	Partial mixing	Exhaust ON / ERV OFF	ERV ON / Exhaust OFF
3	Partial mixing	ERV ON / Exhaust OFF	Exhaust ON / ERV OFF
4	No mixing	ERV ON / Exhaust OFF	Exhaust ON / ERV OFF
5	No mixing	Exhaust ON / ERV OFF	ERV ON / Exhaust OFF

The continuous exhaust ventilation flow was adjusted to meet the ASHRAE Standard 62.2-2015 continuous fan flow rate calculated based on the liveable floor area and number of bedrooms in the CCHT twin houses, and set at approximatively 95 cfm for the exhaust fan in the master bathroom and the ERV's supply and exhaust airflows.

2.3 Performance Measurements

The testing approach was a combination of air leakage characterization (fan depressurization tests), envelope differential pressures (with respect to outdoor, attic and garage), perfluorocarbon tracer gases (PFT's) to determine zone air change rates, multi-zone sampling of VOCs and aldehydes to determine the indoor air quality impacts as function of the ventilation system operation, and finally impact on whole building energy consumption. The ambient test conditions, such as flow rates through ventilation system components (exhaust fan and ERV), temperature distributions in various zones throughout the house and weather conditions were continuously monitored and recorded during each test to establish the complete experimental context for each test's results. Airtightness is the fundamental house property that impacts infiltration (movement of air through leaks, cracks, or other adventitious openings in the building envelope). It was necessary to characterize the airtightness of the two houses. This was accomplished by conducting a fan depressurization test using an orifice blower door according to the ASTM test method E 779-03 (ASTM, 2003). The blower tests were done during the baseline test to confirm that the two houses have similar air leakage for accurate comparisons in term of the impact of ventilation strategy on the IAQ.

The house's envelope pressure distribution were monitored continuously and recorded during each test to establish the complete experimental context of each test's results and data interpretation. The differential house envelope pressures were measured using bi-directional Veris PX Series differential air pressure transducer sensors with data loggers. The differential pressures were measured on all floors (basement, first floor and second floor) in designated zone and facades with respect to outside, garage and attic, as shown in Table 2.

Table 2 – Location of envelope differential pressure measurements

Floor	Zone / Facade	Differential Pressure
Basement	North Façade	Indoor to Outdoor
Main Floor	Living Room / North Façade	Indoor to Outdoor
	Dining Room / South Façade	Indoor to Outdoor
	Hallway / Entry	Indoor to Garage
Second Floor	Master Bedroom / North Façade	Indoor to Outdoor
	Bedroom 2 / North Façade	Indoor to Outdoor
	Bedroom 3 / South Facade	Indoor to Outdoor
	Hallway	Indoor to Attic

A passive perfluorocarbon tracer gas method developed by NRC was used to measure the air change rate in House 1 (M24-B) and House 2 (M24-C). All sources were made with a glass vial (2, 7 or 15 mL) and a septum (silicone lined with polytetrafluoroethylene, silicone rubber or polydimethyl silicone membrane). The difference in the vial size and septum (material and thickness) led to different source rates. In addition to PFTs, two VOCs α-pinene (aPin) and deuterated toluene (tolune-d8; dTol) were deployed to determine the difference in indoor air quality for different ventilation settings. The actual source rate was determined based on the weight difference of a source before and after each test. PFT sources were placed in four zones (basement, 1st floor, 2nd floor, and master bedroom). PFTs and VOCs were sampled with sorbent tubes filled with Carbopack B (CB). CB tubes were deployed in duplicates in each zone (basement - middle, 1st floor – kitchen, 2nd floor – bedroom 2 and master bedroom) for passive sampling with the sampling side tubes left open for 7 days. CB tubes were analyzed by NRC's chemical Lab with the thermal desorption/gas chromatography/mass spectrometry (TD/GC/MS) system, including a Markes' Unity Series 2 thermal desorber coupled to a multi-tube autosampler ULTRA, an Agilent 6890A Gas Chromatograph equipped with a DB-624 capillary column, and a 5973N Mass Selective Detector.

Formaldehyde (HCHO) passive sampling was conducted in the basement (unfinished), main floor (dining area), master bedroom (second floor), Attic, Garage and outdoor of each house and during the 5 test cases. Formaldehyde/Aldehydes passive sampling was done using three 2,4-dinitrophenylhydrazine (DNPH) cartridges; one for field blank and two for duplicate samples. Two openings of cartridges were left open for 7 days. At the end of the sampling period, the DNPH cartridges were sent back to NRC's chemical lab for analysis. Analysis of formaldehyde was performed according to ASTM D5197 and EPA TO - 11a.

Changes in house performance due to the two ventilation systems was also addressed through comparison of energy, in addition to ventilation and IAQ of the two houses; house operated with balanced energy recovery system to the house performance operated with continuous exhaust ventilation system in master bathroom. The recorded houses energy consumptions included; heating energy consumption (furnace natural gas consumption), furnace fans electrical consumption, exhaust fans electrical consumption and dual core ERV fans electrical consumption.

2.4 Results and Analysis

Air leakage characterization of the two twin houses was conducted using a fan depressurization test (blower door). Same calibrated fan was used, and pressure measurement was recorded in each house with respect to outside. The ACH_{50} value is the number of air changes that will occur in one hour with a 50 Pa pressure difference being applied uniformly across the building envelope. It is the metric of interest when one is referring to the building airtightness. Table 3 outlines the relevant parameters that were measured for the air leakage test conducted in both test houses. The airtightness of both research houses is essentially the same, with a 3.4% difference.

Table 3 - Reported blower door test results for each house

Parameter	House 1 (M24-B)	House 2 (M24-C)
Q_{50} (CFM)	859 ± 7	827 ± 8
ACH_{50} (h^{-1})	1.79	1.73

The Natural Resources Canada ecoENERGY (NRCan) retrofit program tested thousands of houses in Ottawa following renovations designed to improve the building airtightness. As a comparison they found that the mean airtightness (ACH_{50}) for the homes built between 1990 and 1999, the same decade of construction as the CCHT test houses, was 4.48 (NRCan 2015). Therefore one should consider both CCHT houses to be very airtight.

The ERVs installed in both houses were well balanced and the exhaust fans in master bathrooms (in both houses) were set to exhaust the same airflow as the ERV units. The exhaust airflow by the fans installed in the master bathroom of both houses was measured using a calibrated airflow element (Nailor type) and the data was recorded using a Hobo data logger. The supply airflow to the furnace return air plenum from the ERV installed in both houses, and the exhaust airflow from bathrooms and kitchen through the ERV were measured using calibrated airflow stations (Nailor type) and recorded by the houses data acquisition units. The measured exhaust airflows from master bathroom and ERV's supply/exhaust airflows in both houses are statistically summarized in Table 4.

Table 4: Measured Supply and Exhaust Airflows

Test	Airflow location	House 1 (M24-B)				House 2 (M24-C)			
		Min.	**Max.**	**Mean**	**Stdv**	**Min.**	**Max.**	**Mean**	**Stdv**
1	Exhaust Fan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Exhaust ERV	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Supply ERV	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	Exhaust Fan	86.3	112.9	<u>102.7</u>	4.0	0.0	0.0	0.0	0.0
	Exhaust ERV	0.0	0.0	0.0	0.0	78.8	113.5	<u>98.9</u>	3.9
	Supply ERV	0.0	0.0	0.0	0.0	80.4	111.2	<u>95.6</u>	4.5
3	Exhaust Fan	0.0	0.0	0.0	0.0	85.1	116.2	<u>102.4</u>	4.3
	Exhaust ERV	88.2	109.7	<u>99.0</u>	1.6	0.0	0.0	0.0	0.0
	Supply ERV	77.6	112.6	<u>95.0</u>	2.3	0.0	0.0	0.0	0.0
4	Exhaust Fan	0.0	0.0	0.0	0.0	85.0	110.1	<u>98.5</u>	3.4
	Exhaust ERV	85.9	111.0	<u>98.2</u>	2.0	0.0	0.0	0.0	0.0
	Supply ERV	77.7	113.1	<u>94.9</u>	2.9	0.0	0.0	0.0	0.0
5	Exhaust Fan	81.8	113.7	<u>97.5</u>	3.7	0.0	0.0	0.0	0.0
	Exhaust ERV	0.0	0.0	0.0	0.0	82.2	110.2	<u>98.5</u>	2.5
	Supply ERV	0.0	0.0	0.0	0.0	79.0	114.0	<u>96.4</u>	3.5

Underlined numbers are the mean values of measured airflow over the each testing period

If the building envelope is tight, there is a possibility that negative pressure can be created inside the building. Supply air enters the building in an uncontrolled manner and may be pulled in from relatively undesirable areas such as garages, musty basements (or crawl spaces) or dusty attics (Barley, 2002). This study included measurement of the envelope differential pressure between the indoor and the outdoors. A positive reading of the indoor pressure means that the indoor is pressurized, and a negative value means the house is depressurized. The differential pressures were measured for 5 side-by-side tested cases and a typical weekly plot for test 5 undertaken with no mixing is presented in Figure 2.

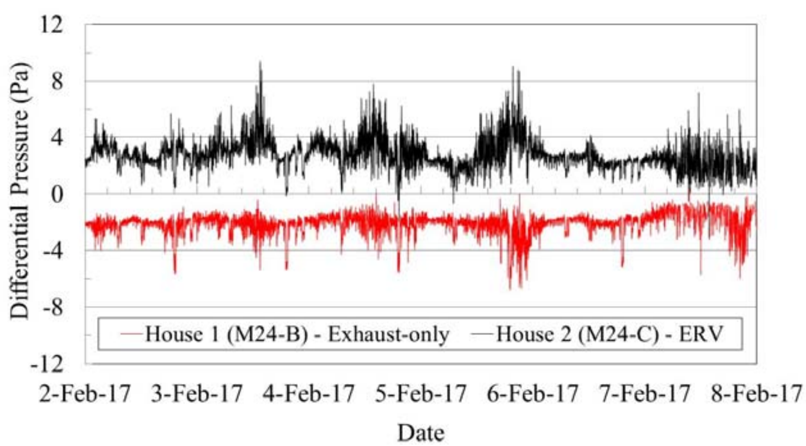

Figure 2 – Whole House Envelope Differential Pressure from Test 5

The measured average envelope differential pressures to outdoor (including adjacent zones) and to only outdoor (excluding attic and garage) are presented in Table 5 and Table 6. Except for Test 1 where the two houses were operated without mechanical ventilation, the results for the 4 Tests with mechanical ventilation (Tests 2, 3, 4 and 5) have shown that the house with an ERV (with balanced ventilation) had an overall positive indoor pressure showing that the house was slightly pressurized. However, the house with a continuous exhaust from master bathroom had an overall negative indoor pressure, showing that the house was depressurized

Table 5 – Average Measured Indoor Pressures to Outdoor (including adjacent zones)

House	Test 1	Test 2	Test 3	Test 4	Test 5
M24-B	+0.6 (Baseline)	-1.5 (Exhaust)	+0.7 (ERV)	+0.8 (ERV)	-1.8 (Exhaust)
M24-C	+0.7 (Baseline)	+2.8 (ERV)	-1.3 (Exhaust)	-0.9 (Exhaust)	+2.8 (ERV)

Table 6 - Average Measure Indoor Pressures to Outdoor (excluding adjacent zones)

House	Test 1	Test 2	Test 3	Test 4	Test 5
M24-B	+0.5 (Baseline)	-2.9 (Exhaust)	+1.0 (ERV)	+1.2 (ERV)	-2.4 (Exhaust)
M24-C	+0.3 (Baseline)	+2.2 (ERV)	-1.7 (Exhaust)	-1.4 (Exhaust)	+2.8 (ERV)

The air change rate calculated from the PFT concentrations and emission rates, assuming the house is well-mixed single zone, are summarized in Table 7. The mean value of all PFT gases deployed in the house was used as the representative concentration. The house volume was assumed to be 794.3 m^3. The baseline test (Test 1) shows that the air change rates in M24-B and C were similar under the same conditions, i.e., when there was no ventilation and no mixing. Under the partial mixing winter conditions (Test 2 and 3), the air change rate was 0.33 or 0.34 h^{-1} with ERV and 0.28 or 0.29 h^{-1} with exhaust-only ventilation. Under the no-mixing and winter conditions (Test 4 and 5), the air change rate was also higher with ERV than with exhaust-only ventilation (0.38 vs 0.36; 0.49 vs. 0.38 h^{-1}). The air change rate in the house with ERV was greater than that with exhaust-only ventilation by 6 to 28% in heating season 2016/2017 regardless of the mixing condition (no mixing, partial mixing).

Table 7: Air Change Rate (h^{-1}) for a whole House

House	Test 1	Test 2	Test 3	Test 4	Test 5
M24-B	0.06 (Baseline)	0.28 (Exhaust)	0.34 (ERV)	0.38 (ERV)	0.38 (Exhaust)
M24-C	0.07 (Baseline)	0.33 (ERV)	0.29 (Exhaust)	0.36 (Exhaust)	0.49 (ERV)
Percent Difference[1]	9%	15%	16%	6%	28%

[1] $(ACH_{ERV} – ACH_{EXH})/ACH_{EXH}*100$

The two added VOC sources of α-pinene (aPin) and deuterated toluene (tolune-d8; dTol) were placed in four zones, basement (middle), 1st floor (kitchen/dining area), 2nd floor (bedroom 2 and master bedroom). The average indoor concentrations during the Baseline test and the four ventilation systems are illustrated graphically in Figure 3.

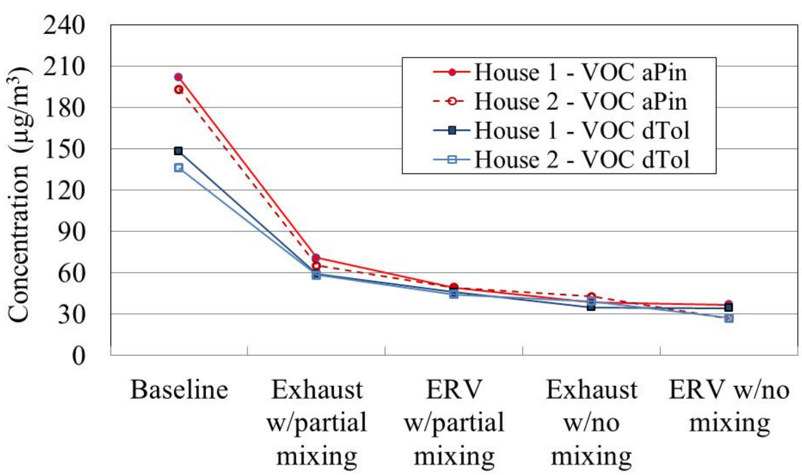

Figure 3 – Average Indoor α-pinene and Deuterated Toluene Concentration by Ventilation System Type

Both tested ventilation systems reduced the aPin and dTol concentrations below the Baseline concentrations which were roughly 5-7 times higher. ERV system reduced the zonal indoor aPin and dTol concentrations the most. For both houses operated with partial mixing, the ERV system showed a 22% to 78% reduction in aPin concentration and a 14% to 62% reduction in dTol concentration over exhaust-only ventilation system. When the two houses were operated without mixing, ERV system showed an 8% to 89% reduction in aPin concentration and a 17% to 76% in dTol over Exhaust ventilation system. In average for both houses (operated with partial or no mixing), the ERV system showed an average 5% to 60% reduction of aPin and an average 3% to 45% reduction of dTol over Exhaust-only ventilation system.

Formaldehyde was sampled in the Basement, Main Floor and Second Floor (Master bedroom and Bedroom 2) over a week testing periods. The average indoor concentrations during the Baseline test and the four ventilation systems are illustrated graphically in Figure 4. Outdoor formaldehyde concentrations were measured beside the twin houses located in Ottawa and were 2.4-2.6 μg/m^3. Both tested ventilation systems reduced the formaldehyde concentration below the indoor Baseline concentration which was roughly 14 times higher than what was measured outdoor. Exhaust-only ventilation reduced the indoor formaldehyde concentration the least. Exhaust-only with partial mixing and without mixing showed no significant difference in reducing the formaldehyde concentration. However, ERV without mixing showed a significant reduction in formaldehyde concentration over ERV with partial mixing because ERV exhausted un-mixed stale air directly from kitchen and bathroom on the Main floor and bathrooms in on the Second floor. For both houses operated with partial mixing, the ERV system showed an average 10% to 14% reduction in formaldehyde concentration over exhaust-only ventilation system. When the two houses were operated without mixing, ERV system showed an average 51% to 66% reduction over Exhaust ventilation system. In general for both houses (operated with partial or no mixing), the Exhaust system showed a zonal 7% to 61% reduction of formaldehyde and the ERV system showed a 13% to 89% reduction of formaldehyde over Baseline.

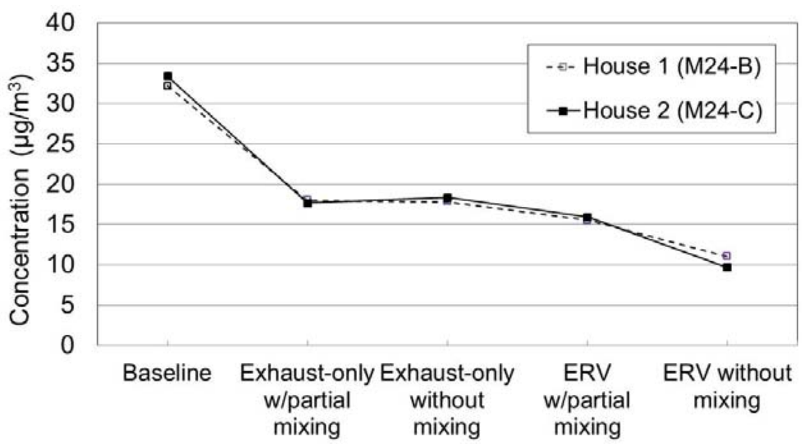

Figure 4 – Average Indoor Formaldehyde Concentration by Ventilation System Type

A summary of the weekly energy analysis results from the side-by-side testing at the Canadian Centre for Housing Technology (CCHT) in winter 2016/17 is provided in Table 8. The energy analysis compared the total space heating and ventilation energy used in the houses during the various testing scenarios. The energy analysis took into account the small difference in energy performance of the twin houses when both are operating under benchmark conditions. The expected space heating and ventilation consumption in benchmark configuration (i.e. expected consumption if operating the benchmark ERV equipment) is calculated first then from this the overall energy savings when operating the bathroom exhaust fan is calculated. Savings are calculated by subtracting the measured House with exhaust-only experiment consumption from the calculated House with ERV benchmark consumption. The average weekly energy savings when operating the ERV compared to running the benchmark ERV for Tests 2 to 5 varied between -3.6% to -8.5%. The negative indicates that the overall space heating energy consumption when operating the exhaust fan from master bathroom was greater than when operating the ERV (an energy penalty) despite the fact that the exhaust only electrical use was less than the ERV electrical use. This is logical because space heating is a much greater load compared to ventilation and with exhaust only ventilation, the make-up air would come from uncontrolled and unconditioned air leaking into the houses, whereas with the ERV heat is recovered from the warm exhaust to condition the controlled supply from the outside, lowering the overall space heating energy.

Table 8: Weekly Average Space Heating and Ventilation Total Energy Consumption

Test	House 1 (M24-B)				House 2 (M24-C)				Savings [MJ]	Savings [%]
	Furnace Natural Gas [ft^3]	Furnace Fan [kWh]	Exhaust ERV Fan(s) [kWh]	Total [MJ] ([1])	Furnace Natural Gas [ft^3]	Furnace Fan [kWh]	Exhaust ERV Fan(s) [kWh]	Total [MJ] ([2])		
2	456.7	2.323	0.600	493.0 (475.9)	453.8	2.367	1.111	491.9 (n/a)	-17.1	-3.5%
3	314.4	1.562	0.992	341.3 (n/a)	348.6	1.731	0.600	376.7 (354.2)	-22.5	-6.3%
4	338.9	1.585	1.006	367.3 (n/a)	382.6	1.846	0.600	413.0 (380.8)	-32.2	-8.5%
5	411.0	1.980	0.600	443.4 (426.9)	408.0	1.991	1.016	441.8 (n/a)	-16.5	-3.9%

[1] expected House 1 energy consumption in a benchmark configuration [MJ]
[2] expected House 2 energy consumption in a benchmark configuration [MJ]

3 CONCLUSIONS

The paper presented a portion of results from a research project intended to develop a better understanding of whole-building ventilation systems effectiveness and distribution in R-2000 home to demonstrated and quantify the IAQ-related benefits of balanced ventilation system. In general the side-by-side testing showed that the single-point exhaust ventilation from master bathroom was inferior as a whole-house ventilation strategy with negative indoor pressures. In contrast, the balanced (ERV) ventilation system was able to provide a slightly positive indoor pressure and that there is a significant benefit to drawing outside air from a known outdoor location, and filtering and distributing that air. The PFT testing and analysis was required to compare the air change rates which were higher for a house operated with balance ventilation system by 6% to 28%. Drawing air through the houses enclosure and adjacent spaces via exhaust ventilation showed higher concentrations of formaldehyde and the two added VOCs aPin and dTol. The ERV system showed a significant reduction in formaldehyde concentration over the baseline and exhaust tests. In general for both houses, the ERV system showed a 10% to 66% reduction in formaldehyde concentration over exhaust. In terms of VOCS, the ERV system showed also a significant reduction in aPin and dTol concentrations over the Baseline and exhaust tests. For both house operated with ERV system showed an 8% to 89% reduction in aPin concentration and a 14% to 76% reduction in dTol concentration over exhaust ventilation system. The study also confirmed that a balanced ventilation system is more energy efficient with a weekly energy savings between 3.9% and 8.5%. This research provides justification for the installation of a balanced ventilation system (positive pressure ventilation system) and supports credit for fully-distributed whole-building ventilation systems compared to lower performance systems.

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5 REFERENCES

ASHRAE Standard 62.2 (2015). *Ventilation and Acceptable Ondoor Air Quality in Low-Rise Residential Buildngs*. ASHRAE, Atkanta, GA.

ASTM (2003). *American Society for Testing and Materials' Test Method E 779-03*.

Barley, C.D. (2002). *Barriers to Improved ventilation in Priduction Housing. Proceedings of Indoor Air (9th International Conference on Indoor Air Quality and Climate). Monterey, CA. Vol. 2. pp. 896-901.*

Canadian Centre for Hosuing Techmology (CCHT). www.ccht-cctr.gc.ca

Natural Resources Canada (2015). Office of Energy Efficiency, accessed 5; http://www.nrcan.gc.ca/energy/efficiency/housing/home-improvments/5003.

Rudd, A.F. (2000).*Measurement of ventilation and Interzonal distribution in single-family homes. ASHRAE Transactions, 106: 709.*

Russel, M. (2005). *Review of Residential ventilation Technologies. LBNL 57730, Lawrence berkeley National laboratory.*

Sherman, M. (2007). *Energy impact of Residential ventilation Norms in the United States. LNBL 62341, Lawrence berkeley National Laboratory, Environmental Energy Technologies division.f the Original Peoples of Northern Canada.* Montreal: McGill/Queen's University Press for the Arctic Insitute of North America.

Vornanen-Winqvist, C. (2017). *The Effect of Positive Pressure on Indoor Air Quality in a Deeply Renovated School Building - a case study 11th Nordic Symposium on Buildings Physics, NSB2017, Trondheim, Norway.*

Wray, C.P. (2000). Selecting Whole-house Ventilation Strategies to Meet Proposed Standard 62.2: Energy Cost Considerations. ASHRAE Transactions, 106: 681.