Evaluation study of the performance of dual core energy recovery system for dwellings in the Arctic

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Abstract. In extreme cold climates, conventional single core heat/energy recovery ventilators experience major problems with ice formation on the extracted airside and frequently under-perform or fail. A dual core design could overcome the performance of single core design units and meet the rigorous requirement for operation in the North. The evaluation of the performance of a dual core unit was undertaken using dual environmental chambers capable of reproducing the typical outdoor and indoor conditions with regard to temperature and relative humidity. Experiments were conducted under a range of outdoor cold temperatures, and indoor conditions identified for housing in the Arctic. The dual core ERV was found to be capable of withstanding a temperature of down to -37°C without deteriorating its thermal performance, and therefore was more frost-tolerant than conventional single core units. In conclusion, the dual core design system could be a feasible option for extreme cold climates.

Keywords: Energy recovery ventilator, Dual core, Ventilation, Residential, Arctic.

1 Introduction

Effective ventilation is essential to provide acceptable indoor air quality (IAQ) and control moisture in homes. However, ensuring proper ventilation while minimizing energy costs in dwellings can be a challenge in Canada's North and Far North (Arctic) due to several factors including a harsh cold climate and frequent overcrowding. Space heating requires an enormous amount of energy in an extremely cold climate with long winters. To reduce energy costs building techniques have been improved in the Arctic regions making building envelopes more air tight to decrease the heating demand. As homes across Canada's North are built tighter, there has been an increase in the poor IAQ. Without ventilation air, carbon dioxide, odors, dust, airborne pollutants and excess humidity are kept indoors, potentially causing or aggravating problems to occupants' health and comfort, and encouraging mold growth. An increasingly common method to provide a required ventilation rate, control moisture build-up and reduce energy costs is to install a balanced ventilation system that uses a heat or enthalpy recovery ventilator (HRV or ERV). HRV/ERV ventilation systems (single core design) installed in dwellings in Canada's North and Far North frequently under-perform and fail [1, 2]. Ventilation of houses can be very problematic in the North where frosting poses a significant challenge for the heat/energy exchangers. The design winter temperatures in the far North are much colder than the outdoor temperature of -25°C that is typically used by HRV/ERV manufacturers for their certified products rating. Frost formation in exchangers is common in cold regions where the outdoor temperature is below -10°C for the majority of the cold season. Conventional problems created by the formation of frost in heat/energy exchangers [3] are:

- Partial or full blockage of air flow passages,
- Increase in pressure drop through the exchanger or decrease in airflow rate,
- Increase in electric power for the fans,
- Decrease in the heat transfer rate between the two air streams and
- Cold draughts in the space due to low supply air temperatures.

In cold climates, conventional HRVs/ERVs require a defrost strategy to remove frost that can form within the air-to-air heat exchanger core. The conventional frost protection mechanisms in single core units can incidentally create an intermittent ventilation system that causes cross contamination of exhaust and supply air streams. These shortcomings can undermine the outdoor air requirements of residential ventilation standard [4], a residential ventilation standard commonly used as a baseline for building codes and programs. This can result in uncomfortable and unhealthy living conditions for occupants. At present, there are no HRVs/ERVs specifically designed and manufactured to meet the rigorous requirements for operation in the Far North. A new design of energy recovery ventilation system with dual core exchangers addresses the frost protection concerns by periodically warming the return air through one of the two heat exchanger cores while the outdoor air gains heat from the other. The new design could overcome the challenges faced by conventional single core heat/energy recovery ventilators in the Arctic. This paper presents the performance evaluation results from laboratory testing of the dual core unit for realistic Northern indoor and outdoor conditions.

2 Methodology

The experimental work consisted of laboratory testing of a dual core energy recovery unit using a combination of two environmental chambers and an HRV/ERV test rig.

2.1 Tested Technology

A dual core energy recovery unit is based on the working principle of cyclic storage and release of heat in the heat exchanger cores of corrugated sheets alternately exposed to exhaust and intake air. The unit includes a supply and an exhaust fan and two cores filled with specially corrugated 0.7 mm thick aluminum plates which act as heat accumulators. In between the cores is a patented damper section which changes over every 60 seconds to periodically direct warm air through one of the two cores while outside air gains heat in the other core. Before each fan is a filter section to filter the air. Heat recovery is automatically activated when called upon. The schematic of the dual core unit with the two sequences is presented in Fig. 1, with a description of the 2 sequences below.

Sequence 1 – Exhaust air (RA) charges *Core B* with heat from return warm air (RA) from indoor and *Core A* discharges heat to supply air (SA).

Sequence 2 – Exhaust air (RA) charges *Core A* with heat from return warm air (RA) from indoor and *Core B* discharges heat to supply air (SA).

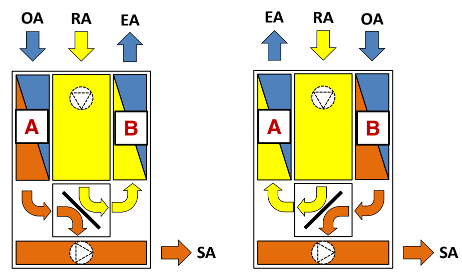

Fig. 1. Principle of function – sequence 1 (left) and sequence 2 (right)

In addition to the innovative heat recovery strategy described above control logics are implemented to regulate internal damper to ensure that comfortable air delivery temperatures are achieved in all conditions. The damper is controlled by the 2 internal thermostats GT1 in the supply air and GT2 in the exhaust air. GT1 is set to 15°C; GT2 is set to 20°C. The sequence of operation is as follows:

1. If exhaust air temperature is lower than 20°C, unit in energy recovery mode (cycling every 60 seconds).
2. If exhaust air temperature is higher than 20°C and supply air temperature higher than 15°C, unit in free cooling mode (cycling every 3 hours). (This mode is not expected to be used often in Arctic conditions. Monitoring in the Arctic planned for future phases should help verify this.)
3. If exhaust air temperature is higher than 20°C and supply air temperature lower than 15°C, unit in energy recovery mode until the supply air temperature becomes higher than 15°C then it will revert to free cooling mode.

2.2 Experimental Facility

The following experimental facility and associated setup were used to perform a first round of short-term cold-climate performance tests of the dual core heat exchange unit under controlled laboratory conditions at NRC installations in Ottawa. The NRC's Environmental Chambers are capable of simulating interior and exterior climatic conditions over an extended period of time. The exterior climatic conditions can be varied over a range of - 40 to + 40 ± 1.0°C with the capability of maintaining a steady state set point. Simulated interior climatic conditions can be varied from 15°C to 30 ± 1.0°C with the capability of maintaining a steady state ambient humidity (30 to 60 % RH). The HRV/ERV test rig shown in Fig. 2 and installed between the indoor and outdoor climatic chambers consisted of four rigid straight ducts for airflow measurements, connected to the unit under test and to the climatic chambers using flex ducts. The ducts are insulated with a low vapour permeability sleeve to minimize heat transfer and vapour accumulation in these long ducts.

Fig. 2. HRV/ERV test rig

2.3 Instrumentation

Air is drawn from two environmental chambers at desired conditions. In order to determine the efficiency and the conditions leading to frosting in the dual core unit, several properties are measured at different locations in the test facility. Two airflows were measured using Nailor type airflow elements. Airflow elements were installed in the supply (SA) and exhaust (RA) ducts to measure the mass flow rates of dry air in the supply and return airstreams. Pressure taps were placed at the inlet and outlet of unit (SA, RA, EA, OA) to measure the static pressures, connected by PVC tubes to the pressure transducers integrated in a designed pressure transducer box. The air temperature and relative humidity were measured using RH and T probes, calibrated over a temperature range of -40°C to +40°C and over an RH range of 10% to 90%. The temperature and RH were measured at the inlets and outlets of the unit. The required sensors were calibrated; specifications of the sensors used to measure temperature, relative humidity, pressure and flow, and their accuracy are presented in Table 1.

Table 1. Specifications of instrumentation

Type	Model	Range	Accuracy
RH&T probe	Vaisala HMP60	-40°C to +40°C	±0.2°C
		10 to 90%	±3%
Pressure transducer	Setra C264	0 – 125 Pa/-125 to +125 Pa	±1% FS
Airflow element	6” Nailor 36FMS	30 to 200 cfm	±5%

3 Test Procedure

A series of experiments were conducted to gather data on the thermal/ventilation behavior and performance of the tested unit when subjected to steady state climatic indoor and outdoor conditions. Collected data was used to calculate the apparent sensible/total effectiveness and assess the impact of potential build-up of frost on the thermal and ventilation performance of the dual core technology. The research was limited to the evaluation of innovative technologies for the Arctic, thus the testing was done for the heating mode only. The living conditions in the north shows that the homes can be more crowded and that the level of indoor relative humidity would be higher than in homes located in the south part of Canada. The two main air properties that may affect frosting are temperature at supply inlet (from outdoor) and RH at the air exhaust inlet (from indoor). The indoor air temperature (exhaust inlet) is kept constant in all experiments, and RH at the supply inlet (from outdoor) does not play a significant role in the frosting. The conditions in the indoor chamber were set at realistic indoor conditions in northern homes. The temperatures in the outdoor chamber were varied in a range from +10°C to -35°C to challenge the test unit with extreme cold conditions. The experimental evaluation of the performance of a dual core unit was done with supply and exhaust airflows calculated for the Canadian Centre for Housing Technologies (CCHT) houses [5]. Outdoor air shall be mechanically supplied to each dwelling unit using a ventilation system providing no less than the rate specified by Eq. (1) taking into account people and house air needs [4].

$$Q_{tot} = 0.03A_{floor} + 7.5(N_{br} + 1) \quad (1)$$

Where Q_{tot} is the required outdoor ventilation flow rate, A_{floor} is the floor area and N_{br} is the number of bedrooms, not to be less than one.

The CCHT twin houses have a floor area of 210 m^2 (2260 ft^2) with 4 bedrooms, which require a total ventilation rate of 47.2 L/s (105 cfm). The dual core unit was tested at balanced supply/exhaust airflows at 47.2 ±2.4 L/s (105 ±5 cfm) calculated using Eq. (1), and following the heating mode experimental design presented in Table 2. Nine tests were undertaken between October 17th and 31st, 2016 with identified Northern indoor conditions of 25°C and 55% RH. After each test the outdoor chamber was reset at a temperature higher than zero to allow the meltdown of any potential frost build up in the two heat exchangers before the next run. This allowed the same initial condition at the start of each test; i.e., consistently no presence of frost in heat exchangers at the start of each test permits comparison between test results.

Table 2. Experimental design

Test	Indoor T [°C] / RH [%]	Outdoor T [°C]	Duration [hr]
1	25°C / 55%	10	7
2		0	7
3		-5	7
4		-10	7
5		-15	8
6		-20	8.5
7		-25	8.5
8		-30	9
9		-35	14

4 Data Reduction

The performance of the dual-core unit is primarily determined by its effectiveness (sensible and total) as described in ventilation and certification standard [6-8], its pressure drop and mass flow characteristics, and supply air temperature to indoor.

The heat exchanger effectiveness includes the following two terms:
Apparent Sensible Effectiveness (ASE) - The measured temperature rise of the supply airstream divided by the difference between the outdoor temperature and entering exhaust system air temperature, then multiplied by the ratio of mass flow rate of the supply airflow divided by the mass flow rate of the lower of the supply or exhaust system airflows.
Apparent Total Effectiveness (ATE) - The measured enthalpy change (sensible plus latent) of the supply airstream divided by the difference between the outdoor enthalpy and entering exhaust system enthalpy, then multiplied by the ratio of the supply airflow divided by the mass flow rate of the lower of the supply or exhaust airflows.

The temperature and relative humidity across the dual core were used to estimate the sensible and total (enthalpy) efficiencies. The supply and exhaust flows were assumed equal (based on balancing the flows at the beginning of the test). The sensible effectiveness and total effectiveness can be calculated using Eq. (2) and are more equivalent to the apparent sensible or total effectiveness because the heat transfer from each fan or through the cases is disregarded.

$$\varepsilon = \frac{m_s(X_{SI} - X_{SO})}{m_{min}(X_{SI} - X_{EI})} \tag{2}$$

Where ε is either the sensible, latent, or total heat effectiveness, X is either, the humidity ratio, w, the total enthalpy, h or the dry-bulb temperature, T, respectively, at the supply inlet (SI), supply outlet (SO) and Exhaust inlet (EI). m_s is the mass flow rate of the supply air, m_e is the mass flow rate of the exhaust air and m_{min} is the minimum value of either m_s or m_e.

5 Results

A total of 9 tests were performed to investigate the performance of the dual core unit under heating mode with northern indoor conditions. Each test started with initial parameters that posed no risk of frosting (outdoor chamber at T > 10°C). Outdoor/supply temperatures are then lowered for each subsequent test to increase the possibility of frosting. In all experiments, the exhaust inlet conditions (return air temperatures from indoors) were maintained at 25°C and ~55% RH. The outdoor temperature varied between +10°C and -37°C and the supply inlet temperature to the unit varied between +8°C and -17°C. The mass flow rate of dry air was ~47.2±2.4 L/s (~100±5 cfm) for both supply and return airstreams.

5.1 Airflow

The supply and exhaust airflows measured during the test done with the coldest outdoor temperature of -35°C are presented in Fig. 3. The results showed a limited decrease in supply and return airflows over time at low outdoor temperature. The decrease started at outdoor temperatures below -20°C and for testing period longer than 7 hours. The longest test period over 14 hours and at an outdoor temperature of -35°C, the decrease of flows are more pronounced and could be caused by frost occurrence in the heat exchangers. The mass flow rate is reduced as ice or frost forms within the heat exchangers at the exhaust side. The supply and return flows could decrease further for longer test period under extreme cold outdoor conditions. The time it would take to choke the flow completely, assuming linearity of the result, could be only confirmed through testing done for more than 14 hours or through extended monitoring under extreme cold conditions in the North.

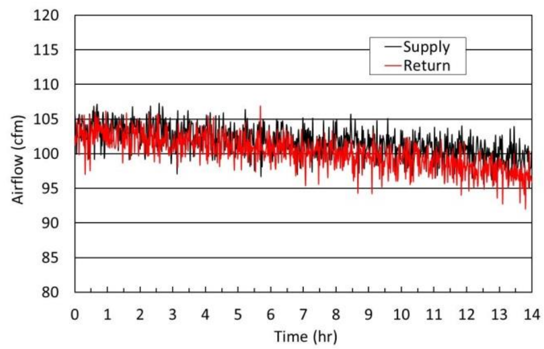

Fig. 3. Measured supply airflow rate at outdoor temperature of -35°C

5.2 Effectiveness

The calculated apparent sensible efficiencies calculated for the Northern operating indoor conditions are presented in Fig. 4 nine outdoor temperatures varying from -35°C to +10°C. The calculated values ranged from 79% to 93%. The calculated values for different outdoor conditions were in a same order around 85%, much higher than the claimed sensible efficiencies for conventional single core HRVs/ERVs.

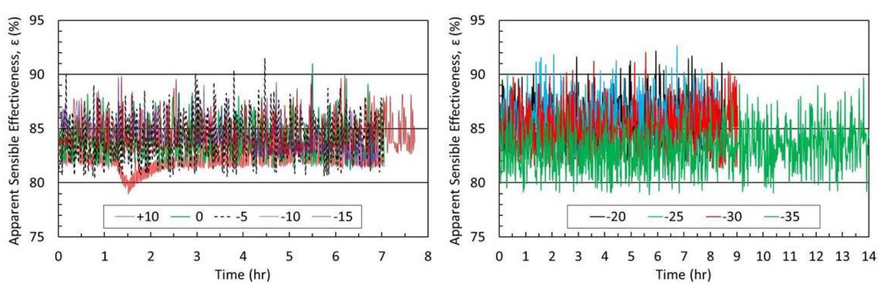

Fig. 4. Apparent sensible effectiveness

The calculated apparent total (sensible + latent) efficiencies for the same Northern operating indoor conditions and outdoor temperatures are presented in Fig. 5 and the calculated values ranged from 59% to 91%. Same trend has been seen for the total effectiveness increasing at lower outdoor temperatures and getting closer to the sensible values at outdoor temperatures below -20°C. The results showed that the sensible effectiveness is stable (no reduction) with supply air temperature (outdoor temperature) variations. However, the results showed an improvement of the apparent total effectiveness with decreased supply outdoor temperature (decreased outdoor temperature). This could be explained by the fact the total effectiveness depend on the latent heat (moisture in the air) and with the dual core technology, condensation forms on the exhausting heat exchangers (melting the frost build-up by the exhaust warm humid air). When the cycle changes, the outdoor air is passed over the heat exchanger and that moisture is added back to the airstream. The indoor humidity is retained by this technology and reduces the need for added humidity in the conditioned home.

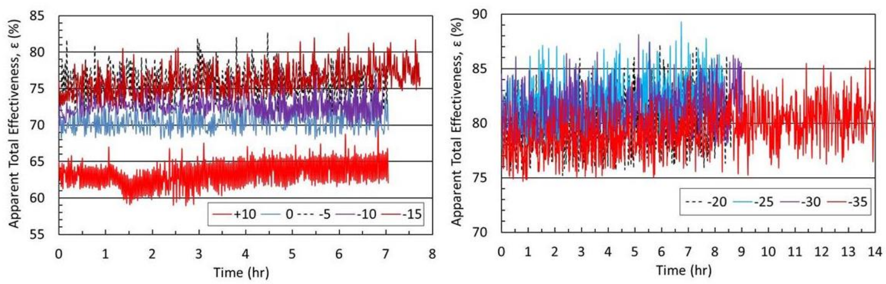

Fig. 5. Apparent total effectiveness

5.3 Supply air temperature to indoor

The efficiency of heat/energy recovery systems should be high enough that tempering of the supply air would not be needed to maintain comfortable interior conditions, even in cold weather. The measured supply air temperature for Northern operating indoor conditions to the indoor are presented in Fig. 6 and the values ranged from 15.3°C to 22.8°C and averaged from 15.5°C to 22.6°C.

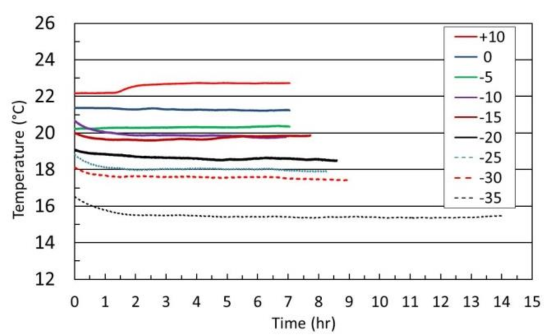

Fig. 6. Supply temperature to indoor with Northern indoor conditions

As expected again, the values decreased with decreasing supply temperature (and outdoor temperature), providing a supply air temperature as low as 15.5°C which is fairly low and will require either a provision for tempering by blending the supply air with room air or preheating before direct delivery to the occupied spaces.

5.4 Frost Occurrence

Depending on exposure time and physical circumstances, frost forming on cold heat exchanger surfaces may enhance or reduce heat fluxes while airflow rates and pressure drop may remain nearly constant or sometimes change drastically. Many parameters may affect frosting, including air inlet conditions, flow rates, exchanger effectiveness and design. In this research, and air flow rates were kept constant. The two main air properties are the supply inlet temperature (T_{OA}) and exhaust inlet relative humidity (RH_{RA}). T_{RA} is kept constant in all experiments, and RH_{OA} does not play a significant role in frosting. A visual observation was conducted to show if there was or not presence of frost in the two heat exchangers. At the end of each test, the frontal door of the dual core unit was opened and photos were taken to visualize potential frost formation. Photos taken during tests are presented in Fig. 7 for the top part (frontal) of the exchangers. The photos show formation of frost on the top front part starting at outdoor temperature condition of -25°C, and no frost formation on the lower front portion of the exchangers. The length of the frontal portion with frost formation increased at lower outdoor temperature (OA), with frost formation on almost the half top of the front of exchangers at -35°C.

Fig. 7. Photos of the front top of the heat exchangers

Although photos taken at temperatures below -25°C may look like the heat exchangers are fully blocked, the frost build up shown in those photos does not extend through the depth of the heat exchangers in the third dimension. The frost formation was largely concentrated on the front and sides of the heat exchangers, with a small amount on the back and only a very small amount at the top of the heat exchangers where most of the flow occurs. The frost formation was limited to front and sides of the heat exchangers and almost none at the inlet/outlet (of the airstreams) and inside (between plates), confirming the limited flow reduction at low outdoor temperatures.

6 Overall Thermal Performance

The average values of the calculated sensible and total efficiencies, and measured supply air temperatures from tests done with Northern indoor conditions (25°C and

55% RH) are presented in Fig. 8 versus outdoor temperature. The average value of the sensible effectiveness was constant and did not vary with the outdoor temperature. However, the total effectiveness increased with lower outdoor temperature which was likely due to condensation formed on the exhausting heat exchanger. When the cycle changed, the outdoor air was passed over the heat exchanger and that moisture was added back to the airstream. The lowest supply air temperature of 15.5°C was reached at outdoor temperature of -35°C which would require provision of tempering the supply air before delivery to the indoor spaces. The majority of HRVs/ERVs are designed with a single core (one heat exchanger) and few new models with dual core that have two heat exchangers in series or two plate heat exchangers in parallel. They are designed for a range of airflows to cover wide residential applications. The claimed apparent sensible efficiencies provided by manufacturers are from certification tests (under very controlled indoor and outdoor conditions) done at the low speed (lowest airflow) and at outdoor temperature of 0°C (mandatory) and -25°C if requested by the manufacturers.

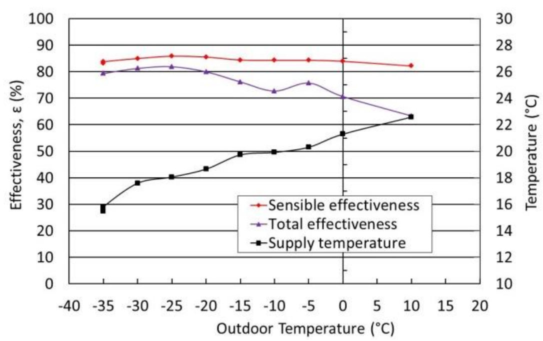

Fig. 8. Average efficiencies and supply temperatures for a range of outdoor temperatures

The claimed apparent sensible efficiencies for single core HRVs/ERVs varied between 73% and 84% at their lowest flows and at outdoor temperature of 0°C. These efficiencies decreased at higher flows down to ~70% and at lower outdoor temperature of -25°C to 76% (lowest flow) when provided. The calculated apparent sensible efficiencies from experimental data obtained for a dual core unit at a rate of airflow of 100 cfm were between 84% and 86% at 0°C, 65% and 86% at -20°C, -25°C, between 84% and 86% at -30°C and between 83% and 87% at -35°C. In general the NRC calculated values were higher than claimed values at 0°C and much higher (10-15% higher) than the few values claimed for outdoor temperature at -25°C.

7 Conclusion

Laboratory testing has shown that a dual core energy recovery unit designed with a damper that periodically directs warm air through one of the two heat cores, is capable of continuously addressing the frost protection concerns for identified northern indoor conditions of 25°C and 55% and outdoor temperature as low as -37°C.

The calculated apparent sensible and total efficiencies were much higher than values claimed for available single core heat/energy recovery technologies at not only 0°C and low fan speed, but also at colder outdoor temperature of -25°C and below.
The dual core unit was found to be capable of operating at a temperature as low as -37°C without deterioration in its thermal performance, and therefore was more frost-tolerant than conventional single core units. The dual core unit also achieved a supply air temperature above 15°C at the lowest outdoor temperature of -37°C. Provision of tempering by blending the supply air with room air or through pre-heating before delivery from ventilation duct might be required for greater indoor comfort in extreme cold conditions. The need for pre-heating will be assessed under extreme climate conditions, over the next phases of this project.The dual core design system could be a feasible option for extreme cold climates. However, extended monitoring of the technology in harsh cold climate is recommended to prove its performance and resilience in Canada's Far North.

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