A COMPARTMENTALIZATION & VENTILATION SYSTEM RETROFIT STRATEGY FOR HIGH-RISE RESIDENTIAL BUILDINGS IN COLD CLIMATES

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ABSTRACT

This research proposes an alternative rehabilitation strategy for aging high-rise multi-unit residential buildings (MURBs) involving suite compartmentalization and decentralizing the ventilation system. Energy efficiency retrofits of MURBs today tend to focus on increasing the thermal performance and air-tightness of the enclosure, which neglects the inherent inefficiency and ineffectiveness of pressurized corridor ventilation systems, and often amplifies deficiencies. An alternative approach is to isolate the suites from the corridors, and install balanced heat recovery ventilators in each. Ventilation can then be maintained at design rates, and regulated according to need. This proposed retrofit was investigated for an existing high-rise MURB in Vancouver. Computer simulation using EnergyPlus™ (v.8.4.0) was used to examine the impact of the proposed retrofit on the case study building. Results show annual heating energy decreased by 51% and overall GHG emissions decreased by 29%. The main benefit of the proposed retrofit, however, is improved zone air distribution of the mechanical ventilation system. Because building enclosure air-tightness improvements can negatively impact air distribution in buildings with pressurized corridor ventilation systems, the proposed retrofit should be applied in combination with, or before, an enclosure retrofit. Thermal resilience should also improve, with longer passive surviveability durations from a reduction in uncontrolled air leakage induced by stack effect.

INTRODUCTION

Background and problem

Most existing high-rise multi-unit residential buildings (MURBs) in Canada use a central ventilation system to pressurize the common corridors on each floor with fresh air, relying on air leakage past the door undercuts and out through the exterior envelope to ventilate the suites. Wind pressures, stack effect, and window operation all work to disrupt airflow patterns, leading to either wasteful over-ventilation or unhealthy under-ventilation of most suites. It has long been known in the building science community that these systems are both inefficient and ineffective. Research by Canada Mortgage & Housing Corporation showed that "conventional corridor air supply and bathroom/kitchen exhaust systems do not, and cannot, ventilate individual apartments" (CMHC, 2003). This conclusion was based on the determination that standard building design and construction practices have done little to prevent uncontrolled airflows within a MURB, or through its enclosure. In order to try to compensate for poor ventilation distribution performance, central ventilation systems are generally oversized in an attempt to simply overcome other driving forces on airflow. A study of 10 Canadian high-rise MURBs built in the early 1990's found design airflows ranging from 154% to 461% of the minimum outdoor air capacity requirements of ASHRAE Standard 62, with an average of 264% (Edwards 1999). Oversized ventilation systems represent an important energy savings opportunity in building retrofits.

A study of 39 MURBs in BC found that central ventilation systems provided on average 69% of the overall space heating energy (RDH Building Engineering Ltd. 2012). Another study of 13 high-rise MURBs in the Vancouver area concluded that conditioning of the central make-up air accounted for 39% of their total heating energy consumption (Hanam et al. 2011). Measurements at the case study building showed over half the heating energy went to condition this ventilation air, yet as much as 92% of that air leaked outdoors through unintended pathways without reaching the suites (Ricketts and Straube, 2014). This ventilation strategy is relatively energy intensive, yet much of this energy is wasted since not all the air reaches the living spaces it was intended for.

Retrofits of MURBs generally focus on increasing the insulation and air-tightness of the enclosure to improve overall thermal performance. This can amplify the deficiencies of pressurized corridor ventilation systems, worsening indoor air quality (BC Housing 2015). One study examining the effect of enclosure retrofits on six MURBs in Canada showed that the average air leakage rates through the exterior enclosure were reduced by 31% (CMHC, 2013). Although air leakage can be a significant source of energy loss, enclosure air-tightness improvements without ventilation strategy changes will tend to just redirect more ventilation air out through unintended pathways and penetrations.

Case study building

A 13-storey MURB in Vancouver underwent an envelope retrofit in 2012 to improve durability, air-tightness and thermal performance. Various building performance characteristics were measured before and after the retrofit, including air-tightness and energy consumption. Ricketts et al. found that on average only approximately 8% of the mechanical ventilation air was reaching the suites, with the remaining air being lost to the outdoors through unintended pathways (e.g., duct leakage, elevator shaft, stairwell, etc.) (RDH Building Engineering Ltd. 2012). In addition, suites on the lower floors were significantly under-ventilated, and those on the upper floors were over-ventilated, largely due to the upward internal airflow trend caused by stack effect. Figure 1 below illustrates the case study building during and after the enclosure retrofit, as well as the corresponding energy model.

Figure 1: Case study building during and after enclosure retrofit, and corresponding energy model visualization

Retrofit proposal – Suite compartmentalization and in-suite balanced ventilation with heat recovery

An alternative approach to rehabilitating high-rise MURBs is to focus on enabling efficient and effective ventilation. By isolating each suite through air-tightness measures, uncontrolled airflows into and out of the suites is reduced. Stack-induced pressure differentials across the exterior enclosure decrease, causing suite ambient pressure to equalize with atmospheric pressure, thereby reducing airflows in and out through the enclosure.

The central ventilation system delivery rate can be reduced significantly to just the level required to serve the common corridors, resulting in a corresponding decrease in natural gas consumption used to condition the outside air.

Fresh air would then be provided by a dedicated heat recovery ventilator (HRV) in each suite, allowing ventilation rates to be controlled predictably. The HRV's balanced intake and exhaust flows help to avoid pressurization or depressurization, and reduce uncontrolled air leakage. Demand-controlled ventilation is made possible so individual suites are not unnecessarily ventilated while unoccupied. The suite-based system also encourages more energy conscious behaviour as occupants' window and balcony door opening habits would have a greater impact on their utility bills.

Research objective

The objective of this research is to investigate potential impacts of the proposed retrofit strategy on the energy use of a case study MURB in Vancouver. The impact on overall heating energy use, fuel mix, and carbon footprint is examined through computer simulation using a calibrated energy model.

METHOD

Building performance simulation - base model setup

Comprehensive physical and operational characteristics of the building were known from extensive observations and measurements at the site, and these data were incorporated into the EnergyPlus model. Input parameters were based on as-constructed drawings, a complete heating and ventilation equipment inventory, miscellaneous gas and electrical appliances, equipment nameplate data and/or performance spot measurements, operating and occupancy schedules, thermostat set points, and detailed site-based hourly weather data. Mechanical ventilation effectiveness testing results including measured air distribution rates to the corridors and suites were incorporated in the model. The airflow resistance characteristics of the enclosure (flow coefficient and exponent) from fan pressurization and depressurization testing were available, as well as some average pressure differential measurements across the exterior walls, allowing infiltration rates to be estimated for inputs in the model.

Energy end use analysis – utility bills

Monthly energy use data were available for both natural gas and electricity. Natural gas data was broken down by end use for domestic hot water (DHW), makeup air unit (MAU), and fireplaces. Electricity use was divided in two readings – one for all common areas of the building, and one for all suites combined. The proportion of total suite electricity use attributed to heating was estimated by analysing the summertime monthly suite-level electricity on a floor by floor basis, and separating this base load from the total. This approach yielded a better base load estimation than regression analysis against heating degree days for any reasonable balance point temperature.

Calibration procedure

The energy model was calibrated to the above energy end use breakdown according to ASHRAE Guideline 14, using the statistical comparison technique (ANSI/ASHRAE 2002). Unknown parameters were adjusted in successive simulation iterations in order to satisfy the calibration acceptability indices.

A custom weather file was created using data from a weather station located on the roof of the case study building, and simulations during the model calibration stage were run using this weather file.

The simulated natural gas consumption for each sub-metered end use (MAU, DHW, fireplaces) was tuned in first to match the corresponding recorded usage profiles. Calibration to natural gas use was done before electricity use because each sub-metered end use was distinct, with their driving factors fairly well understood. In contrast, the electricity data included many different types of end uses, regulated and unregulated, all lumped together. In addition, the MAU and fireplaces would have a strong influence on the heating energy portion of the electricity data, so their energy profiles needed to be established before the electricity data could be disaggregated with any confidence.

Electricity consumption for the common areas of the building was a fairly steady operational base load easily matched to the metered profile. The weather-dependent heating energy portion of the overall suite-level electricity was separated from the weather-independent base load portion through a floor by floor analysis of summertime electricity use (no air conditioning units were present). Coarse calibration of electricity for heating was done with rate and schedule adjustments to natural ventilation, which was not measured but observed to occur. Fine adjustments were then made to other variables governed by occupant behaviour, such as lighting and equipment usage schedules, to refine the profile shape of both the heating and overall suite-level electricity use together.

An average mechanical ventilation rate of 2.9 L/s per suite and average infiltration rate of 0.3 L/s/m^2 of exterior wall area were used based on measured data.

All energy use profiles fell well within the acceptability indices of +/- 5% mean bias error (MBE) and +/- 15% coefficient of variation (root mean squared error) (CV(RMSE)) for calibration to monthly data. Overall natural gas achieved a 0.7% MBE and 6.8% CV(RMSE), and overall electricity achieved a 0.3% MBE and 8.9% CV(RMSE).

The simulation was run again with a typical meteorological year weather file for the nearby airport (YVR CWEC) in order to produce more typical performance results. Fireplaces and natural ventilation were eliminated from the energy model at this point as they are functions of occupant behaviour, and while necessary for the calibration procedure they are not of particular interest in the comparative analysis.

Modelling of the proposed compartmentalization and ventilation system retrofit

The compartmentalization retrofit of the suites was modelled by eliminating the mechanical ventilation airflow from the corridors. This was determined to be a conservative approach as any conditioned ventilation air which might enter the suites in reality (from opening doors or leakage) would have a negligible effect on their heating load.

Infiltration was adjusted by assuming the average pressure differential across the exterior would decrease from 4 Pa (Gowri et al. 2009) down to 1Pa, and recalculating a new estimated infiltration rate of 0.13 L/s/m^2 using the measured airflow resistance characteristics. Transient increases in infiltration due to wind pressure were simulated using the linear wind coefficient of the ZoneInfiltration object in EnergyPlus. A coefficient of 0.224 was used based on the DOE-2 infiltration model as recommended by Gowri, Winiarski, & Jarnagin (Gowri et al. 2009).

The ventilation system retrofit was modelled by adding a balanced HRV to each suite. The bathroom exhaust fans were eliminated as their function would now be handled by the HRV. Continuous supply and exhaust rates were set to 55 L/s to meet ASHRAE Standard 62.1-2010/2013 and account for a zone air distribution effectiveness factor of 0.8 (ASHRAE 2010). HRV specifications were chosen based on currently available equipment for the design flow rate, with an estimated static pressure of 75Pa, a power draw of 60W, an efficiency of 75%, and a dynamic reset to match the occupancy and area requirements of section 6.2.7.1.2

(ASHRAE 2010). The central ventilation rate was reduced to 0.3 L/s/m^2 to meet guidelines for common corridors (ASHRAE 2010).

RESULTS

Simulation of the proposed retrofit shows a 51% (48.5 ekWh/m^2) reduction in total annual heating energy (Figure 2), with the electrical portion decreasing by 20% (10.5 kWh/m^2), and natural gas component decreasing by 87% (38.0 ekWh/m^2). The proposed retrofit results in an increase in space heating load associated with mechanical ventilation due to the increase in ventilation rate by the HRVs. However this increase is offset by the reduced space heating load due to the decreased infiltration rates predicted, and the significantly reduced natural gas consumption by the MAU now only serving the corridors.

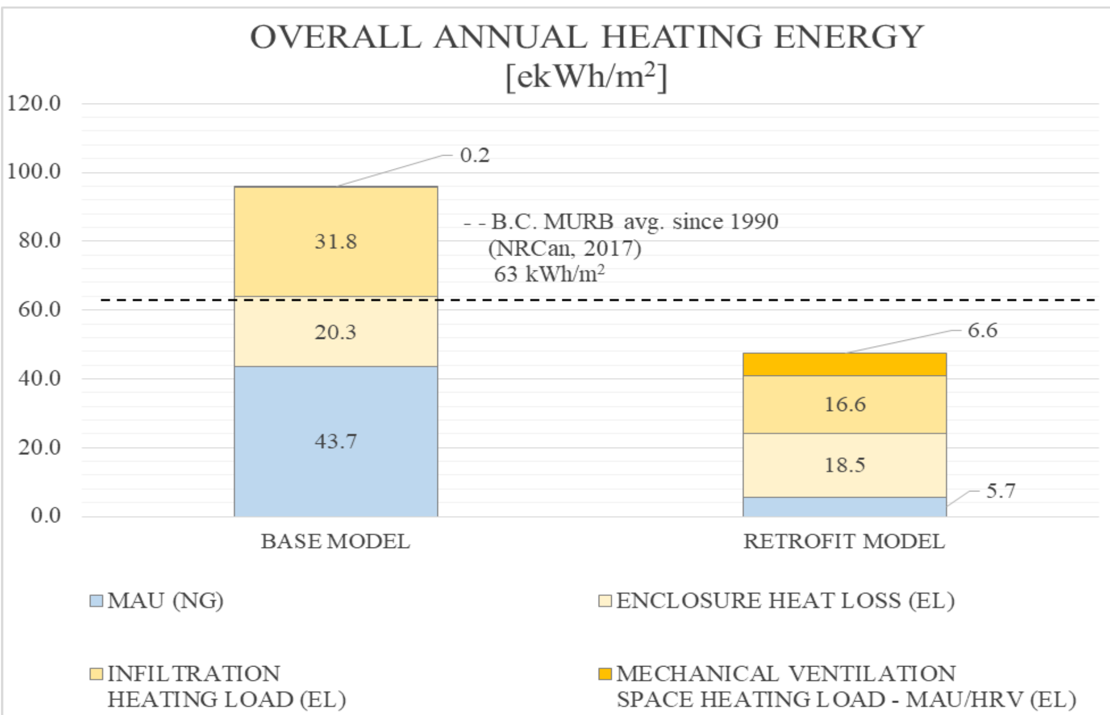

Figure 2: Total annual heating energy breakdown – space heating and mechanical ventilation

Figure 3 below shows the overall annual GHG emissions for the building (all sources), which decreased by 29%, or 20.2 tCO_2e (3.9 $kgCO_2e/m^2$), with total emissions from electricity decreasing by 10% (1.3 tCO_2e, or 0.25 $kgCO_2e/m^2$), and total emissions from natural gas decreasing by 51% (35.5 tCO_2e, or 6.9 $kgCO_2e/m^2$).

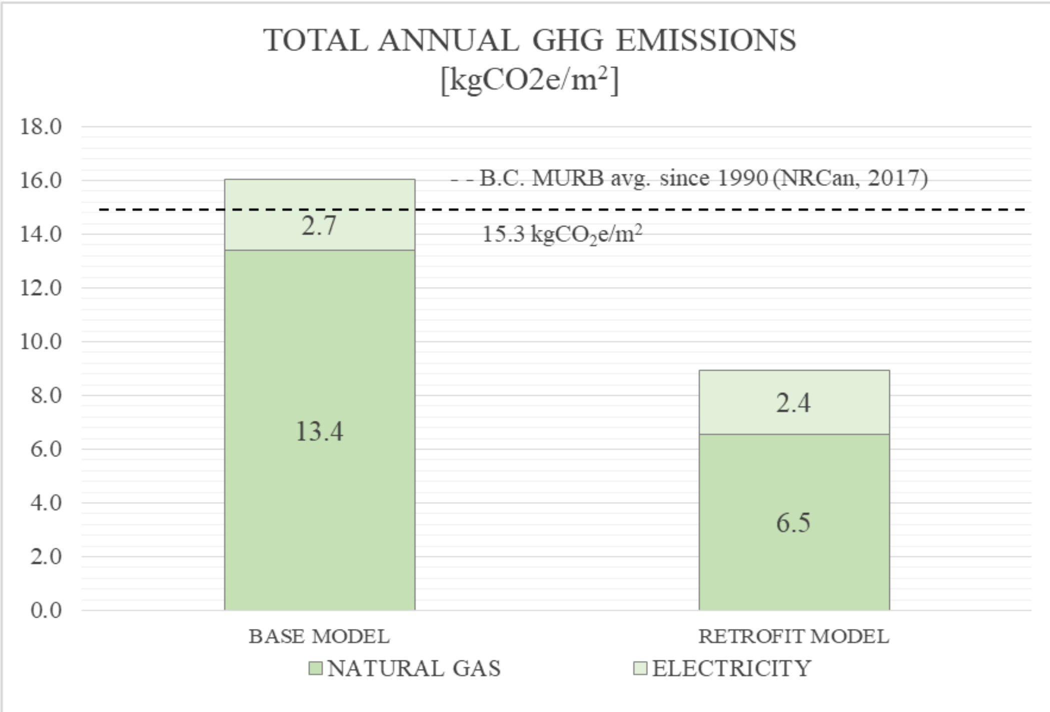

Figure 3: Total annual GHG emissions by fuel type – all sources

DISCUSSION

Because the energy impact of the proposed retrofit is highly dependent on, and sensitive to, the resulting changes in airflow patterns, the base model was calibrated with as much fidelity as possible to the building's actual measured performance. Despite this, it has been demonstrated that it is not possible to fully predict airflow patterns at all times in any high-rise building due to the many fluctuating influences (Ricketts 2014). Best judgement should be used when applying any results presented here to other buildings, or to predict actual future performance.

The main motivation behind the proposed retrofit strategy should however not be to reduce a building's operating cost, especially considering the cost of electricity is generally higher than natural gas, where both are available. The main motivation should be to achieve recommended ventilation rates for each suite, and improve indoor air quality.

Other collateral benefits of the proposed retrofit should also be considered, such as the resulting reduction in GHG emissions.

In 2013, 33% of all natural gas in the province of B.C. was consumed by residential buildings (Statistics Canada, 2014), 58% of which was used for space heating (NRCan, 2017). With apartment buildings alone accounting for 17% of all residential GHG emissions in the province (NRCan, 2017), the proposed retrofit is an opportunity to reduce provincial GHG output and support B.C.'s Greenhouse Gas Reductions Target Act (Province of British Columbia, 2017).

At the national level, residential buildings accounted for 15% of Canada's overall GHG emissions in 2013, with space heating making up 64% of the total residential sector output (NRCan, 2017). Although GHG emission factors and typical fuel mixes vary by province, the benefits of the proposed retrofit would apply across the other provinces of Canada. The GHG emission factor for electricity in B.C. is relatively low at 25 gCO_2e/kWh compared to the 2013 Canadian national average of 150 gCO_2e/kWh (Environment Canada, 2015), so the benefits of the proposed retrofit should be more significant in most other provinces. The GHG reduction potential would also be amplified in the other provinces as their climates are generally much colder than B.C.'s, resulting in higher heating energy demand and greater stack effect pressures. The proposed retrofit is therefore an opportunity to contribute to municipal, provincial, and national GHG emission reduction objectives across the country, and particularly in regions where the majority of grid electricity is produced from renewable sources.

CONCLUSION

A compartmentalization and ventilation system retrofit strategy on a high-rise MURB in Vancouver was simulated, and the impact on overall heating energy, fuel mix, and carbon footprint determined. Results show a decrease in total annual heating energy of 51% (48.5 $ekWh/m^2$). Electricity for heating decreased by 20% (10.5 kWh/m^2), and natural gas for mechanical ventilation decreased by 87% (38.0 $ekWh/m^2$).

The building's overall carbon footprint decreased by 29%, or 20.2 tCO_2e (3.9 $kgCO_2e/m^2$) annually. For regions where the majority of grid electricity is produced from renewable resources, the proposed retrofit is an opportunity to contribute to provincial and national GHG emission reduction objectives.

The findings of this research support the general hypothesis that suite compartmentalization in a high-rise MURB will reduce the energy losses due to uncontrolled airflows. The in-suite ventilation system necessary to supply air to the suites offers further energy savings through heat recovery, as well as enabling demand control to reduce energy while suites are unoccupied.

The main motivation behind the proposed retrofit, however, is to improve mechanical ventilation effectiveness to achieve the recommended ventilation rates, and improve the indoor air quality for the building's occupants. Air-tightness improvements to the building enclosure, when made in isolation, can negatively impact the ventilation air distribution to suites by central corridor pressurization systems. The proposed retrofit measures should therefore be considered with any enclosure retrofit plan for high-rise MURBs.

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