

Airflow in High-rise Multi-unit Residential Buildings with Respect to Ventilation and IAQ

Lorne Ricketts

Student Member ASHRAE

Graham Finch, P.Eng

Associate Member ASHRAE

ABSTRACT

Airflow in to, out of, and within buildings is a fundamental factor of indoor air quality, comfort, durability, and energy consumption. Multi-unit residential buildings are uniquely complex in this respect due to a number of design factors which differentiate them from other building types including the typical inclusion of operable windows, the compartmentalized nature of the interior space, and height. This paper provides the findings of an experimental program conducted at a case study building which was conducted to better understand airflows in multi-unit residential buildings. The analysis includes assessment of the potential impact of the building enclosure energy efficiency upgrades on airflow and ventilation patterns as well as of the performance of the corridor pressurization based ventilation system.

The experimental program carried out at the case study building includes measurement of airflow rates provided by the make-up air unit, measurements of the flow rates between zones of the building using PFT tracer methods, and long-term monitoring of pressure differences at various locations across the exterior enclosure as well as between internal building zones. The interior and exterior environments were also monitored including measurements of temperature, relative humidity, wind speed and direction, and carbon dioxide concentration at various locations throughout the building. Pressure equalized airtightness testing was performed to quantify the resistance to airflow provided by the exterior enclosure and interior compartmentalizing elements.

Overall, this study works to improve the understanding of: airflow patterns in high-rise multi-unit residential buildings; the potential impact of enclosure airtightness improvements on airflow and ventilation patterns; and the performance of corridor pressurization based ventilation systems. This knowledge can then be applied to effective and efficient ventilation strategies to optimize indoor air quality and energy consumption.

INTRODUCTION

Airflow rates in buildings are determined by the interaction of driving forces of airflow with elements that resist airflow as defined by the power law airflow relationship. The driving forces of airflow in buildings are wind, stack effect, and mechanical ventilation systems. These driving forces create pressure differences which drive

airflow in to, out of, and within buildings. These airflows are resisted by the airtightness of building elements including the exterior enclosure and interior compartmentalizing elements such as suite demising walls and floor slabs. Airflow patterns in high-rise multi-unit residential buildings are uniquely complex due to the combination of building height, compartmentalized interior zones, and presence of operable windows. To develop an understanding of airflow patterns in high-rise multi-unit residential buildings (MURBs), including how exterior enclosure retrofits may impact these airflows; an experimental program was carried out at a case study building located in Vancouver, British Columbia.

The building is a 13-storey multi-unit residential building originally constructed in 1986 with a gross floor area of approximately 5,000 m² (54,000 ft²) and 37 residential units with an average of 125 m² (1,340 ft²) each. Glazed windows and doors compose 51% of the vertical enclosure area. The residents of the building are typically 55 years or older and many spend much of their time within their suites, unlike some condominiums which are occupied for fewer hours per day. The building is archetypically representative of much of the existing mid- to high-rise MURB housing stock constructed from the 1970's through 1990's across North America.

The building is ventilated using a corridor pressurization based ventilation system which is specified to provide 1,560 L/s (3,300 ft³/min) to the building which is approximately 40 L/s (90 ft³/min) per suite. This air is supplied to the corridor on each floor via a grille and is intended to pressurize the corridors relative to the adjacent suites and then flow from the corridors to the suites via suite entrance door undercuts. The pressurization of the corridors in this type of system is intended to help control transfer of air contaminants (e.g. cooking odours) between suites.

The original building enclosure consisted from exterior to interior of an exposed concrete wall, 1 ½" of rigid extruded polystyrene insulation installed between steel furring, and interior gypsum board. This wall assembly provided an effective thermal resistance (R-value) of R-4 hr·ft²·°F/Btu considering the exposed slab edges. The windows were non-thermally broken aluminum frame windows with double glazed insulated glazing units (IGUs). The overall building effective R-value was approximately R-2.8 hr·ft²·°F/Btu.

The building underwent a building enclosure retrofit which included the addition of 3 ½" of semi-rigid mineral fiber insulation between low thermally conductive fiberglass clip cladding supports to the exterior of the existing concrete walls. This increased the effective R-value of the wall to R-16 hr·ft²·°F/Btu, a four-fold improvement. The existing windows were replaced with high performance, thermally efficient, triple-glazed fiberglass windows. Importantly, air barrier detailing of these windows and interfaces to the walls was also improved. The overall building effective R-value after the retrofit is approximately R-9.1 hr·ft²·°F/Btu.

METHODOLOGY

To quantify the driving forces, the resistance to airflow, and the resulting pressure field, an experimental testing and monitoring program was developed. This plan included airtightness testing of the exterior building enclosure pre- and post-retrofit, airtightness testing of interior compartmentalizing elements, long-term continuous monitoring of interior and exterior conditions. For practicality, two primary floors were selected (floors 3 and 11) to be the focus of the monitoring and testing efforts, so monitoring and testing were conducted primarily on these and adjacent floors. These floors were selected to be representative of typical floors near the top and bottom of the building.

The make-up air unit intake flow rate was measured using a calibrated fan and custom built flow hood arrangement, and the supply flow rate from the make-up air unit to each corridor was measured using a balometer.

Airflow rates were further measured using the perfluorocarbon tracer (PFT) method developed by Brookhaven National Laboratory and used seven distinct PFTs. (Heiser, & Sullivan, 2002) (D'Ottavio, Senum, & Dietz, 1988) These tracers were absorbed by capillary absorption tube samplers (CATS) over the testing period of one week which was selected to include a typical occupancy pattern. This method provides average flow rates between zones during the testing period.

Airtightness testing was conducted using a pressure-neutralized fan depressurization/pressurization technique. This technique uses multiple flow calibrated door fans to create pressure differences across zone boundaries and across the exterior building enclosure, allowing for the testing of multi-zone buildings such as MURBs. Additionally, by pressure neutralizing adjacent zones in a sequential manner, the airtightness of interior compartmentalizing elements can be determined in addition to the airtightness of the building exterior enclosure (Finch, Straube, & Genge, 2009). A similar method was used to conduct airtightness testing of corridors. During testing of the corridors, components such as suite entrance doors, elevator doors and stairwell doors were sequentially temporarily sealed so the air flow attributable to these components could be determined.

Monitoring equipment was also installed at the case study building. This equipment was designed to monitor interior and exterior environmental conditions. Interior sensors record temperature, relative humidity, carbon dioxide concentrations, and pressure differences between adjacent zones. Exterior environmental conditions including temperature, relative humidity, carbon dioxide concentration, precipitation, wind direction and speed, and solar radiation were monitored. Temperature, relative humidity, and carbon dioxide concentration of the air supplied by the make-up air unit was also monitored. This monitoring data provides quantification of in-service building operating conditions and in particular measurement of indicators of indoor air quality and of the pressure difference between zones.

RESULTS AND DISCUSSION

The make-up air unit intake flow rate was measured directly to be approximately 1,400 L/s (2,900 ft³/min). The flow rates supplied to the corridor on each floor measured from approximately 25 L/s to 125 L/s (50 ft³/min to 250 ft³/min), with a total of approximately 580 L/s (1,200 ft³/min) for all floors combined. This flow total is only 42% of the measured air intake which indicates significant loss of ventilation air. The distribution of this ventilation air to each floor was also found to be uneven, with upper floors receiving on the order of 3 times more ventilation air than lower floors.

Airtightness testing of the corridors indicated that, under test conditions, only approximately 20% of the airflow from the corridors to adjacent zones went through the suite doors and in to the suites, and instead approximately 40% of the air flowed in to the elevator shaft, and 30% flowed in to the stairwell. The remaining 10% takes other flow paths including potentially to the suites through the corridor walls or to the floors above and below. This indicates a significant inefficiency in the building corridor pressurization based ventilation strategy, as a large portion of air supplied to the corridors may leak unintentionally out of the corridors in to the elevator shaft or stairwell instead of flowing in to the suites to provide the intended ventilation rates.

The airflow between zones of the building and from the make-up air unit (MAU) in to the building was measured using the PFT testing during a one week period with typical spring conditions (8°C (46°F) exterior temperature and 3.3 m/s (10.8 ft/s) average wind speed). One of the most significant findings from this testing was

the discrepancy in ventilation rates in suites on upper floors of the building versus lower floors. Upper suites were found to have air change rates of approximately 0.3 to 1.0 per hour, while lower suites ranged from nearly zero to approximately 0.3 indicating that the combination of the ventilation system and the natural driving forces of wind and stack effect is providing significantly different ventilation rates to different parts of the building. This is likely due to a combination of the increased stack effect pressures at the upper floors, increased exposure to wind at the upper floors, and the upper floors being closer to the make-up air unit.

The PFT testing was also used to measure the flow of air from the parking garage below the building in to the occupied zones of the building. The combination of the corridor pressurization system and supplemental exhaust fans in the parking garage is intended to prevent migration of air contaminants from the parking garage in to the building; however, the PFT testing measured flow from the parking garage in to the corridors and suites up to the third floor. This finding indicates that even in relatively mild conditions (8°C exterior temperature) air flows from the parking garage in to the building and may potentially transport air contaminants.

Airtightness testing of the suites also determined that when pressurized relative to adjacent zones pre-retrofit, approximately 58% of air flow was through the exterior enclosure, 19% of airflow is to the suites above and below, 18% is to the corridor, and 5% is to the adjacent suites on the same floor. Post-retrofit, the enclosure airtightness was improved and this airflow became a lower proportion of the total. Post-retrofit, approximately 40% of air flow is through enclosure, 27% is to the suites above and below, 26% is to the corridor, and 7% is to the adjacent suites on the same floor. This indicates that when pressure differences are created across the interior compartmentalizing elements, significant potential exists for stale airflow between suites. The pre- and post-retrofit building enclosure airtightness testing indicated exterior enclosure airtightness of 4.0 L/s·m² (0.78 ft³/min·ft²) and 1.8 L/s·m² (0.36 ft³/min·ft²) at 75 Pa respectively which is an improvement of approximately 54%.

Monitoring of the building pressure field found that an unexpectedly high proportion of induced pressure differences was distributed across the corridor to suite boundary (e.g. suite entrance doors) and a relatively smaller proportion was distributed across the exterior enclosure. Notably, this distribution of pressures does not appear to have changed significantly as a result of the enclosure retrofit despite the improvement in enclosure airtightness. It is theorized that this finding may be due to the widespread use of operable windows (even during cold exterior temperatures) which effectively reduces the airtightness of the enclosure by an order of magnitude and outweighs the improvement in airtightness. This is an important finding unique to MURBs as it is contrary to the common theory that most pressures distribute across the exterior enclosure and that improvements in the enclosure airtightness of buildings may significantly alter pressure fields and airflow patterns, including in particular limiting the flows created by mechanical systems due to increased back pressures.

Monitoring of suite carbon dioxide concentrations found typically higher concentration in lower suites than upper suites, and also found an uneven distribution of carbon dioxide concentrations within a given suite with master bedrooms typically having higher concentrations than the living rooms or near the suite entrance doors. This indicates that the air change rate of lower floor suites is likely less than that of upper floor suites which is consistent with both the ventilation air flow measurements and PFT testing results discussed previously. The uneven distribution within suites indicates that mixing of air within the suites is not sufficient to adequately distribute the ventilation air to all rooms; however, concentrations measured near suite entrance doors were also high which indicates that in many cases the building ventilation system is not providing sufficient ventilation air to

maintain carbon dioxide concentration within the normally acceptable range, even with adequate mixing. As carbon dioxide is an indicator of indoor air quality, and in particular of bio effluents, it is likely that this lack of ventilation and distribution with respect to carbon dioxide indicates a more general problem with indoor air quality.

CONCLUSIONS

The findings at the case-study building indicate that the corridor pressurization based ventilation system provides uneven distribution of ventilation air to the floors and suites of the building, and does not adequately control the flow of air to prevent transfer of air contaminants, in particular from the parking garage. Upper suites of the building were measured to have significantly higher air change rates than lower suites of the building, likely due to the increased magnitude of the driving forces of stack effect, wind, and the mechanical ventilation system for these upper floors.

A large proportion of pressure differences developed by these driving forces was found to distribute across interior compartmentalizing elements, and the enclosure retrofit had little to no observable impact on this distribution. It is theorized that this is likely due to the use of operable windows effectively rendering the airtightness of the exterior enclosure negligible. This finding is contrary to anticipated reduced ventilation rates due to increased back-pressure, and is an important consideration in the design of effective and efficient building ventilation systems.

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