



Pressure Differences and Airtightness in Tall Buildings – Theory & Reality

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ABSTRACT

Airflow in to, out of, and within buildings is a fundamental factor of building design and operation, as building airflow patterns impact occupant health and comfort, building durability, and energy consumption. This airflow is impacted by the airtightness of building elements and pressure differences created by stack effect, wind, and mechanical ventilation systems. Importantly it is the combination of these factors that will determine the resulting airflow patterns at a building.

Airflow theory is relatively well developed, and while it can be quite complex and many unknowns remain, enough is known to assist with the design of mechanical ventilation and airflow control strategies for buildings. This paper provides a summary of key aspects of the relevant theory including analysis of typical pressure differences and distributions of airtightness. The interactions of these factors and the resulting airflows that would be predicted by theory are compared with the measured results at a high-rise multi-unit residential case study building.

The case study includes measurements of airflow rates between zones using perfluorocarbon tracer methods, long-term monitoring of pressure differences, and compartment airtightness testing. Exterior conditions including wind speed and direction, temperature, and relative humidity were monitored using a weather station installed on the roof of the building to allow for evaluation of the interaction between the building and the exterior environment.

Overall, this study aims to improve the general understanding of factors affecting airflows in buildings and how these factors combine to influence the performance of building mechanical ventilation systems. The results of the study allow for general recommendations with regards to the design of ventilation systems, building enclosure airtightness, and compartmentalization strategies.

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1. INTRODUCTION & BACKGROUND


Airflow into, out of, and within buildings is a fundamental factor of building design and operation, as building airflow patterns impact occupant health and comfort, building durability, and energy consumption. Significant work has been conducted to understand airflow in buildings; however, frequently mechanical system designs fail to account for the relatively well understood physics and consequently results in poorly performing building ventilation systems.

Airflow in all contexts is caused by pressure differences across a flow path. Both a pressure difference and flow path are necessary for airflow to occur, and the rate is governed by the magnitude of the pressure difference and the resistance to airflow provided by the flow path. For buildings, pressure differences are created by either the natural causes of wind and stack effect, or by mechanical ventilation systems, which collectively will be referred to as driving forces of airflow. These driving forces move air within and through buildings. This airflow is resisted by various building elements including exterior and interior walls, doors, windows, floors, elevator doors, etc. which for the purposes of this paper will be referred to as *pressure boundaries* because pressure differences can develop across these elements due to the resistance to airflow that they provide. Each aspect of airflow is discussed from both a theoretical perspective and using a case study of a high-rise multi-unit residential building.

The case study building is a 13-storey multi-unit residential building in Vancouver, BC. The building was originally constructed in 1986, has a gross floor area of approximately 5,000 m² (54,000 ft²), and has 37 residential units with an average of 125 m² (1,340 ft²) each. The building is ventilated by an indirect gas-fired make-up air unit on the roof of the building using a corridor-pressurization-based ventilation system. In many respects the case study building is representative of much of the existing mid- to high-rise multi-unit residential housing stock constructed from the 1970's through 1990's across North America.

In the latter half of 2013 the building underwent a significant building enclosure renewal including over-cladding and window replacement. A detailed description of the retrofit and the impact on building energy consumption is detailed in Hanam and Finch (2014), and the potential impact of the retrofit on ventilation rates and airflow patterns is considered where appropriate. Overall the height, typical inclusion of operable windows, and compartmentalized nature of high-rise multi-unit residential buildings makes them both unique and complex, and makes this case study highly appropriate for demonstrating the impact of different factors on airflows in to, out of, and within tall buildings.

To evaluate the performance of the ventilation system and its interaction with other drivers of



airflow at this case study building, an experimental program was developed and implemented which included: measurement of airflows using perfluorocarbon tracer (PFT) gas techniques; measurement of exterior enclosure and interior compartmentalizing element airtightness; and monitoring of pressure differences between building zones. The results of this measurement and testing is compared with airflow theory to provide context for the design of mechanical ventilation systems.

This paper provides a summary of this research work, and the complete study is detailed in Ricketts (2014).

2. AIRTIGHTNESS

Airtightness describes the resistance to airflow provided by pressure boundaries and can be used to control airflow into, out of, and within buildings. These airtight building elements separate the building into spaces which are relatively sealed with respect to air movement. This can include separation of the interior space from the exterior, as well as separation of interior spaces from each other, which is referred to as compartmentalization. To fully understand airflow within and through buildings, characterization of the airtightness of the building pressure boundaries is necessary.

To measure the airtightness of various building elements at the case study building, pressure-neutralized multi-point fan depressurization/pressurization testing was performed. This technique uses multiple fans to sequentially develop and neutralize pressure differences across the exterior enclosure and interior compartmentalizing elements thereby determining the airflow resistance characteristics (i.e. the flow coefficient (C), and the flow exponent (n)) of each of the zone boundaries. This type of testing was performed on 3 corridors (Corridors 3, 9, and 11), 6 suites (suites on Floors 3 and 11), and the top and bottom floors of the building.

To help visualize the overall distribution of airflow paths in the case study building, circles representing the equivalent leakage area of each compartmentalizing element of the exterior enclosure have been overlaid on floor plans for Floor 3 of the building based on a combination of the results of the suite and corridor airtightness testing. These floor plans are provided in Figure 1. Notably, the largest flow paths are typically through the exterior enclosure, through the combination of corridor to suite walls and entrance doors, through elevator doors, and through stairwell doors. Other flow paths are comparatively small.

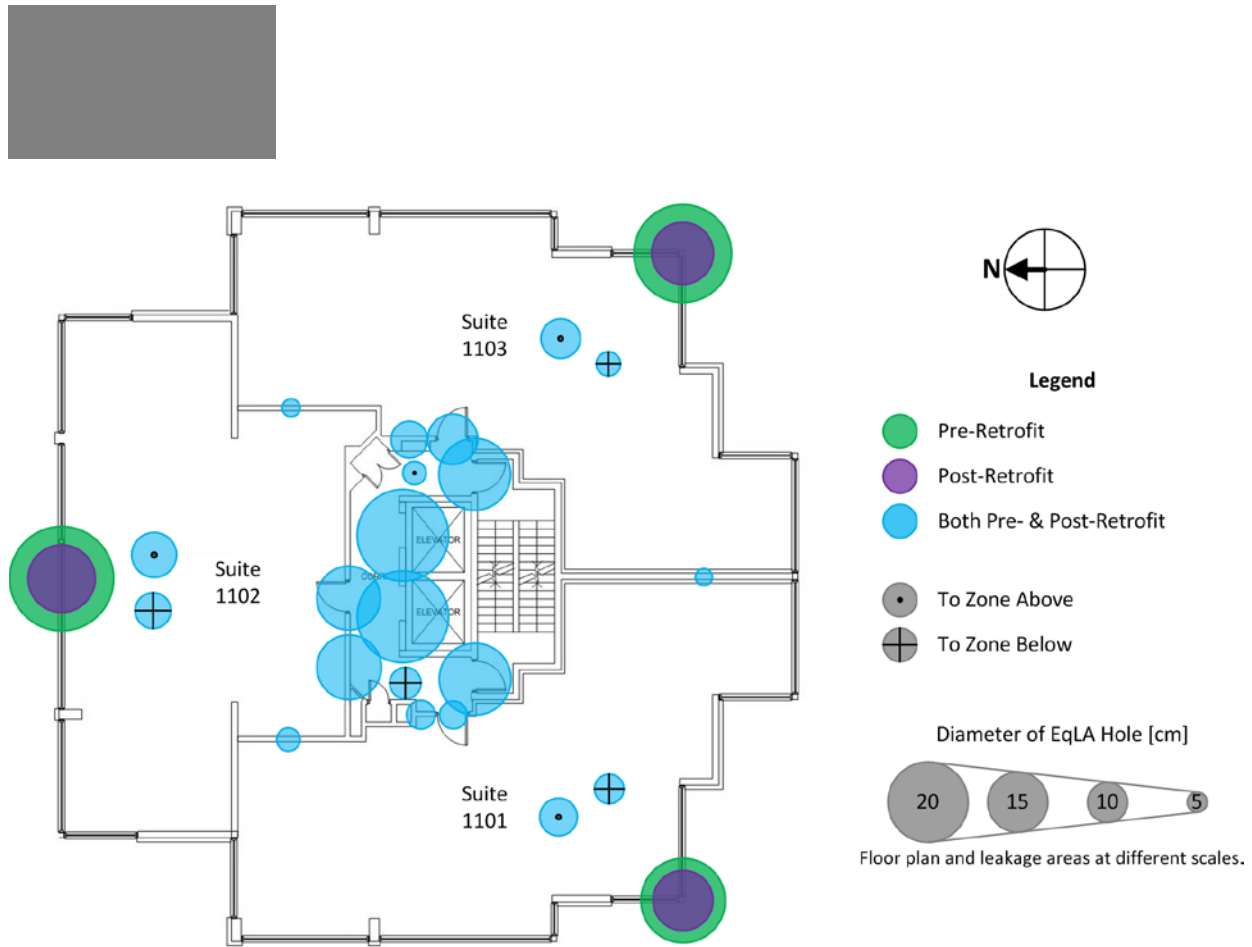



Figure 1: Floor plan of Floor 3 of the case study building showing the equivalent leakage areas of the measured pressure boundaries from the corridor and suite testing

An important finding from the airtightness testing of the case study building was that when the corridor is equally pressurized relative to adjacent zones, only approximately 20% of the airflow paths are directly to the adjacent suites through the suite entrance door. Multi-unit residential buildings are commonly ventilated using a pressurized corridor ventilation system which is intended to provide air to the corridors and the force that air into suites under suite entrance doors; however, if there are significant other flow paths out of the corridor, it is highly likely that this ventilation air will not flow into the suites as intended, resulting in poor performance of the ventilation system. At the case study building, this finding indicates a significant potential for loss of ventilation air to other adjacent spaces such as the stairwells and elevator shafts (70% of total flow), and consequently a significant inefficiency in the system.

Additionally, large flow paths to zones other than the adjacent suites make controlling pressure differences more difficult as the zones are less compartmentalized. Figure 1 shows that significant airflow paths were measured between corridors and suites through both the suite



entrance doors and the surrounding corridor walls. The air leakage through the suite entrance doors is intentional as it provides the path for ventilation air to reach the suites as part of the corridor pressurization system, but also provides a large flow path in the opposite direction when pressure differences reverse. There are also significant flow paths through the concrete floor slabs to the suites above and below. These airflow paths provide a route for unintentional airflows between suites.

Another important factor with respect to airtightness is the presence of operable windows. The airflow through the exterior enclosure at the case study building pre-retrofit was 317 L/s (672 ft³/min) at 75 Pa and post-retrofit was 150 L/s (317 ft³/min) at 75 Pa; however, the opening of operable windows can significantly reduce the resistance to airflow provided by the exterior enclosure. An average operable window at the case study building is approximately 530 mm x 1320 mm (1'9" x 4'4") which corresponds with approximately 4,800 L/s (10,200 ft³/min) at 75 Pa. This flow rate through a completely open window is approximate, but indicates the order of magnitude increase in airflow which can occur through the exterior enclosure when the windows are open compared to when the windows are closed.

These findings at the case study building highlight important design considerations for all buildings. In many cases, the airtightness of interior building elements can be as important to controlling building airflows as is the airtightness of the exterior enclosure, especially when there are operable windows. Airtightness of building elements should be considered a fundamental factor when designing building ventilation systems, and any potential variability in the airtightness of these elements should be taken into account.

3. PRESSURE DIFFERENCES

Airflow into, out of, and within buildings is caused by pressure differences which are created by the natural forces of stack effect and wind, as well as by mechanical ventilation systems. These pressure differences may exist between the exterior and the interior of a building, and between internal building spaces.

3.1 Stack Effect

Stack effect (sometimes also referred to as "chimney effect") is a naturally occurring driving force of airflow created by the difference in air density between the interior of the building and the surrounding exterior environment due primarily to the difference between exterior and interior temperatures.

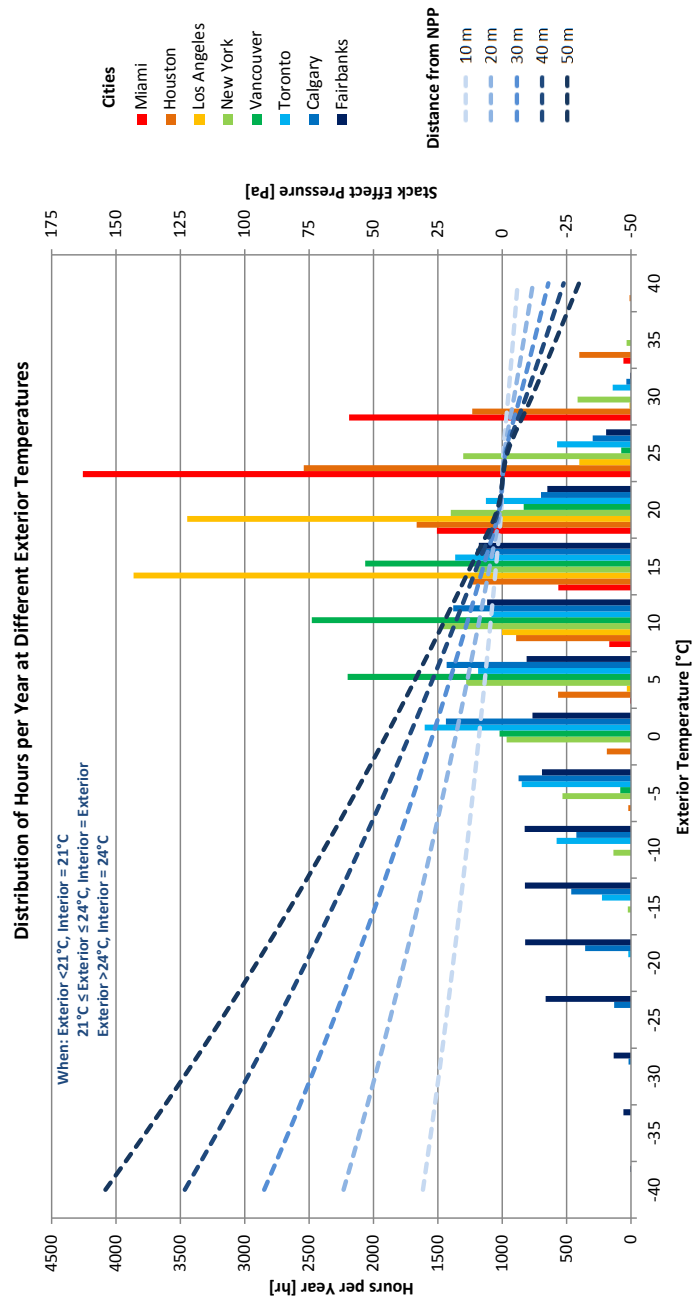


Figure 2: Stack effect pressures overlaid on the number of hours different exterior temperatures occur in eight North American cities



To provide an indication of the magnitude, frequency, and duration of pressure differences created by stack effect, Figure 2 illustrates the number of hours per year that exterior temperatures typically occur in eight North American cities of varying climate. This figure is based on typical meteorological year (TMY) data for locations in the United States, and on Canadian Weather for Energy Calculations (CWECC) data for Canadian locations. Both types of data sets consist of compilations of months of data from various years that are determined to be most representative of typical conditions. (U.S. Department of Energy, 2013) The stack effect pressures for different distances from the NPP are overlaid on Figure 2 assuming an interior temperature of 21°C during cold periods and 24°C during warm periods.

As part of the field study, a long-term monitoring program was implemented which included hourly measurements of pressure differences between various zones of the building as well as across the exterior enclosure. Figure 3 shows the stack effect gradient measured across building elements. The stack effect gradient refers to the difference in pressure differences at two locations divided by the vertical difference between the two locations. Using this metric allows for comparison of the proportion of the theoretical development of stack pressure that acts on different parts of the building.

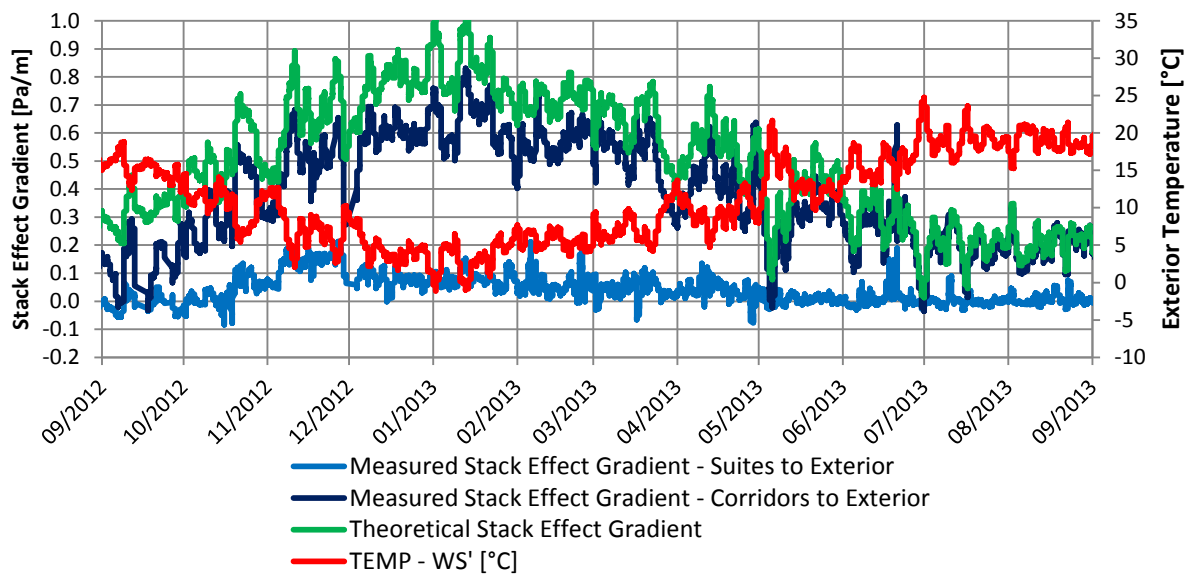


Figure 3: Measured and theoretical (calculated from measured indoor-outdoor temperature difference) stack effect gradients at the case study building



Figure 3 shows that the measured pressure differences are consistent with the pressure differences predicted by theory with increasing pressure difference (i.e. stack effect gradient) during colder periods. Furthermore, the figure shows only a small amount of the pressure difference created by stack effect acts across the exterior enclosure; however, a very large portion of the theoretical stack effect pressure difference acts across the corridor to suite pressure boundary. During a period when the neutral pressure plane location was consistent, from December 1, 2012 to Mar 31, 2013, 9% of the pressure difference due to stack effect acts across the exterior enclosure, and 69% acts across the corridor to suite boundary. This finding is likely due to the opening of operable windows significantly reducing the in-service airtightness of the building enclosure and consequently transferring pressure differences created by stack effect to the most airtight element, which in this case is the walls and doors between the corridors and the suites. This finding has direct implications for the performance of the pressurized corridor based ventilation system, and is an example of how naturally occurring pressure differences can significantly affect interior pressure difference and airflows, and consequently impact the performance of the mechanical ventilation system.

3.2 Wind

Wind is another naturally occurring cause of pressure differences at buildings and typically creates peak pressure differences across the building enclosure, and as such, it is a primary consideration for building structural and air barrier design. On the windward side of a building these pressures typically force air into the building, and on the leeward sides these pressures typically draw air out of a building (Shaw & Tamura, 1977). The pressures created on a building as a result of wind are typically measured as a proportion of stagnation pressure (Cóstola, Blocken, & Hensen, 2009). Stagnation pressure is the static pressure at a stagnation point (i.e. no air velocity) in the air. The stagnation pressure of wind is provided Figure 4, overlaid on the number of hours for which the associated wind speed occurs for six Canadian cities. In this case the cities were selected for differences in wind conditions, rather than for difference in ASHRAE climate zone.

Figure 4 illustrates that during the majority of hours, wind stagnation pressures are relatively low, but that in some cases wind can create very high pressures. This is an important consideration because for ventilation system design it is typically the average operating conditions which are of most importance.

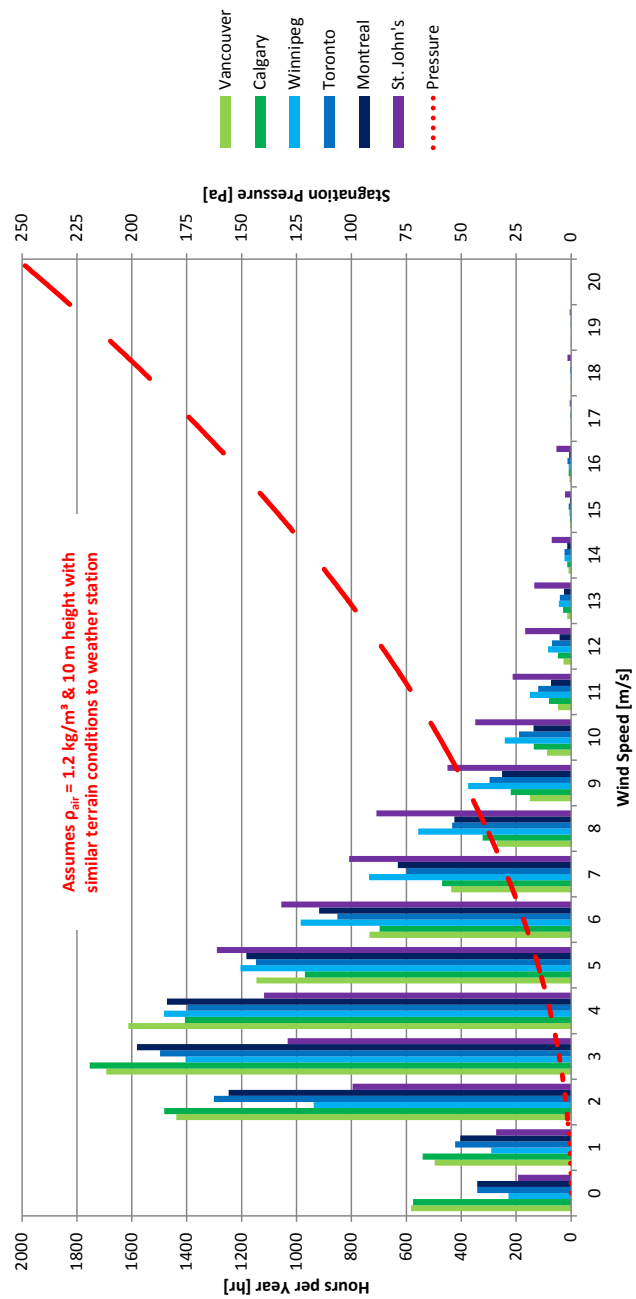


Figure 4: Wind stagnation pressure overlaid on the number of hours of various wind speeds in six Canadian cities



At the case study building, the measured pressure differences created by wind and their impact on ventilation were generally consistent with that predicted by theory, though the significant variability in speed and direction made prediction of the short-term impact at any specific moment difficult. A plot showing an instance when wind created relatively high pressure differences across the suite to corridor pressure boundaries is shown in Figure 5 as an example of the impact of wind at the case study building. This instance of strong winds would likely have created significant airflows into, out of, and within the building; however, wind events such as this typically occurred for short periods.

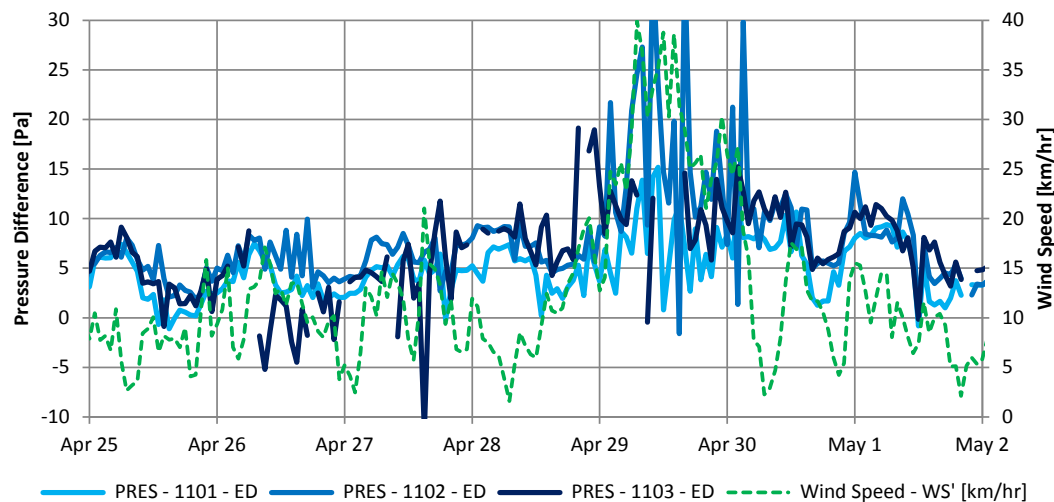


Figure 5: An instance of relatively strong winds significantly increasing the pressure in the corridor relative to the pressure in Suite 1102 (Ricketts & Straube 2014)

3.3 Mechanical Ventilation Systems

Mechanical ventilation systems use fans to create pressure differences to move air into, out of, and within buildings. These systems are intended to ensure that ventilation air of appropriate quantity and quality is provided to all areas of a building so that air contaminants are adequately diluted or removed, and often they are also intended to control the flow of air contaminants between interior buildings zones. In some cases these systems also provide distribution for space heating and/or cooling systems.

A fundamental difference between mechanical systems and the natural driving forces of airflow is that mechanical systems are intentionally included as part of the building design. In some

cases these systems are designed to create pressure difference by exhausting or supplying air from a space at unequal rates, and other times they are designed to operate as balanced systems by exhausting and supplying air to a space at equal rates. When these systems rely upon the development of pressure differences to operate correctly, consideration of their interaction with other driving forces of airflow is necessary.

3.4 Combination of Driving Forces

While each of the driving forces of airflow can be considered in isolation, it is the combination that will determine airflow patterns for a building. The pressure differences created by the driving forces of stack effect, wind, and mechanical ventilation systems can be summed to determine the pressure acting across a building element (ASHRAE, 2009). This concept is illustrated graphically in Figure 6.

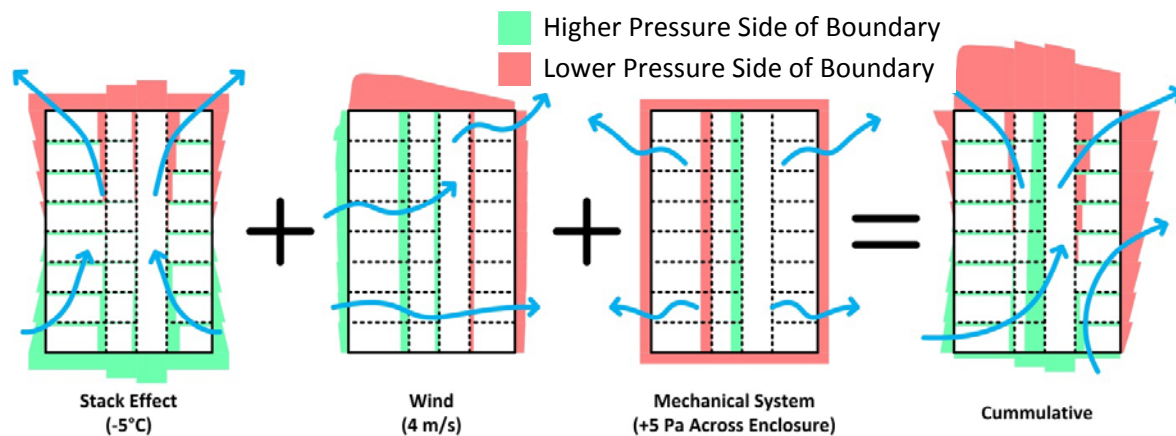


Figure 6: Schematic cumulative effect of driving forces of airflow on a tall building

To examine the relative impact of stack effect and wind on buildings of different heights and located in different climates, the magnitudes of stack effect and wind were calculated for building heights of 20 m, 40 m, 60 m, 80 m, and 100 m (66 ft, 131 ft, 197 ft, 262 ft, and 328 ft) using the maximum pressure created by stack effect (assuming NPP at mid-height of building) and the stagnation pressure of the wind ($C_p = 1$) at the roof of a building. Similar to previous calculations, these calculations use Canadian Weather for Energy Calculations (CWECC) weather data for locations in Canada and typical meteorological year (TMY) data for locations in the United States. (U.S. Department of Energy, 2013) The proportion of the total absolute magnitude of the driving forces attributable to stack effect, wind, and a mechanical pressure of



10 Pa was then determined on an hourly basis for each of these building heights in eight cities in North America. Figure 7 shows the proportion of total pressure difference created by each of the driving forces on an hourly basis for a 40 m (131 ft) tall building in New York. Figure 8 shows the annual average proportion of the absolute magnitude of the total pressure differences created by the driving forces for various building heights in New York, and Figure 9 shows the proportions for a 40 m (131 ft) tall building in each of eight cities with different climates.

Note that Figure 7 through Figure 9 do not indicate the direction of the pressure differences created nor do they indicate the distribution of the pressure differences but instead are intended only to indicate relative magnitudes. As the mechanical ventilation pressure used for these graphs is always 10 Pa, this value can be used in interpreting the graphs to determine the approximate magnitudes of the driving forces.

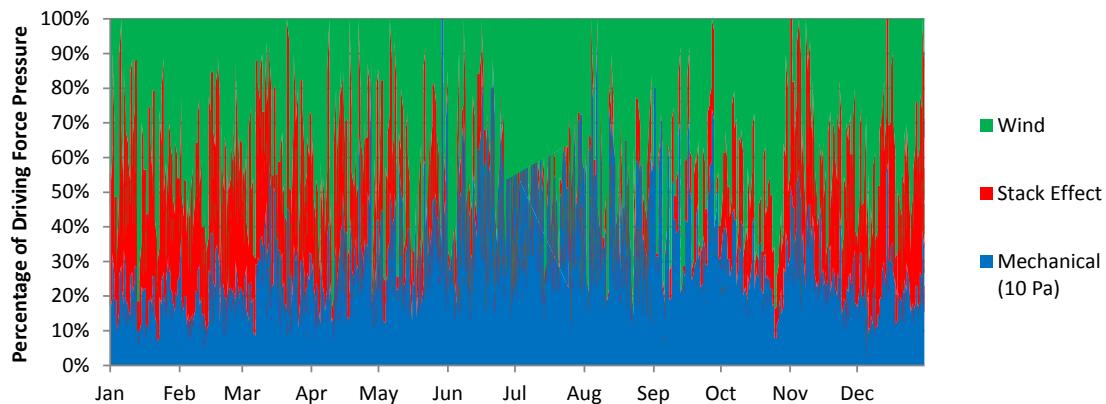


Figure 7: Proportion of absolute pressure difference attributable to each driving force at the top of a 40 m (131 ft) tall building in New York, NY.

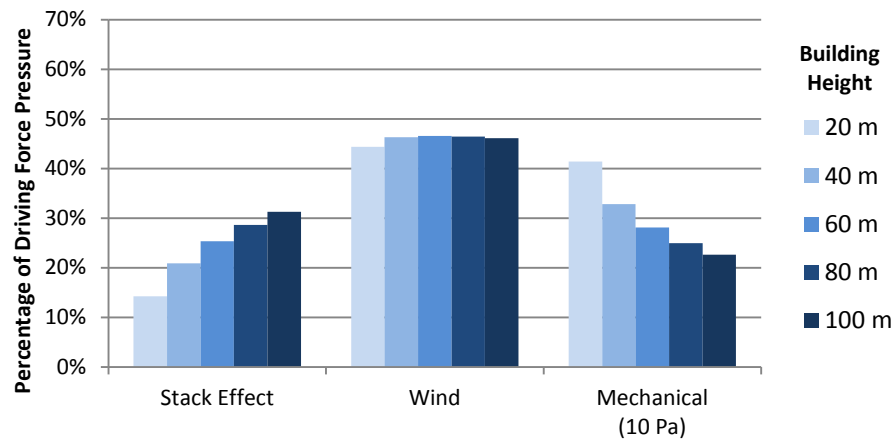


Figure 8: Annual average proportion of total absolute pressure difference attributable to each driving force at the top of a building for various building heights in New York, NY.

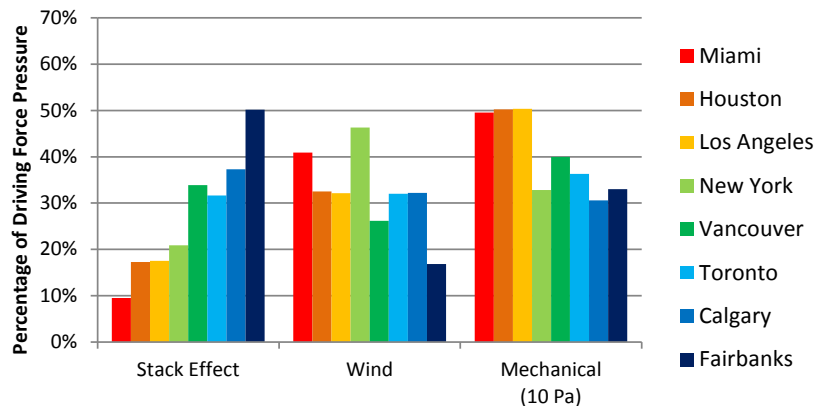


Figure 9: Annual average proportion of total absolute pressure difference attributable to each driving force at the top of a building for various North American cities (Ricketts & Straube 2014)

The combination of the preceding graphs illustrates that, as one would expect, stack effect is a dominant driving force in colder climates and during colder periods of the year, but that in warmer climates wind and mechanical pressures are more likely to dominate. Also, the total magnitude of pressure differences created by stack effect and wind increases with building height, and thus the proportion of pressure difference due to the mechanical ventilation system decreases with building height. Overall, it is possible that any one of the driving forces is dominant in both the short and long-term depending on climate and building height.

4. RESULTING AIRFLOWS AT CASE STUDY BUILDING

To evaluate the in-service effects of the combination of the measured airtightness and pressure differences at the case study building, airflow rates between zones were measured using the perfluorocarbon tracer gas (PFT) testing method developed by Brookhaven National Laboratory. (Heiser, & Sullivan, 2002; D'Ottavio, Senum, & Dietz, 1988) This testing took place for a period of one week from April 10th to 17th, 2013 to capture typical occupancy patterns. For reference, the average exterior temperature during this period was 8°C and the average wind speed was 3.3 m/s. The total air flow rates into the suites as determined by the PFT testing are provided in Figure 10.

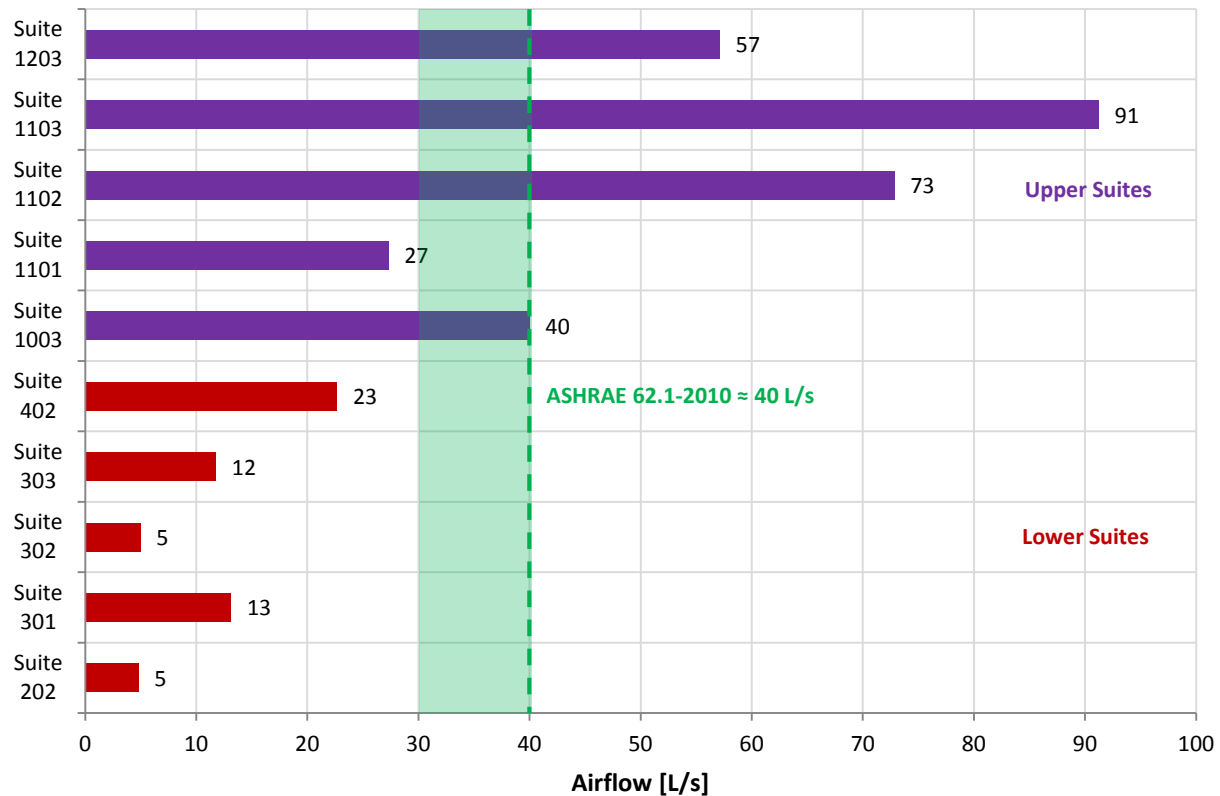


Figure 10: Chart showing the total airflow rate from all sources in to each of the measured suites

Figure 10 indicates that there is an order of magnitude variation in the ventilation rates of the suites at the case study building. Typically, upper suites are over-ventilated and lower suites are



under-ventilated compared to modern ventilation standards. (ASHRAE 62.1-2010) This pattern is consistent with the predicted theoretical impacts of stack effect and wind which would generally reduce the ventilation provided to lower suites as compared to upper suites, especially when the neutral pressure plane is located low in the building, as it is for this case study building. (The neutral pressure plane was measured to be approximately located on Floor 3.)

The findings of the PFT testing are reinforced by the measurement of carbon dioxide concentrations in the suites. These measurements are provided in Figure 11 and indicate that there are significantly higher carbon dioxide concentrations in the lower suites than in the upper suites, and that often the measured levels are above the generally recommended concentration of 1000 ppm.

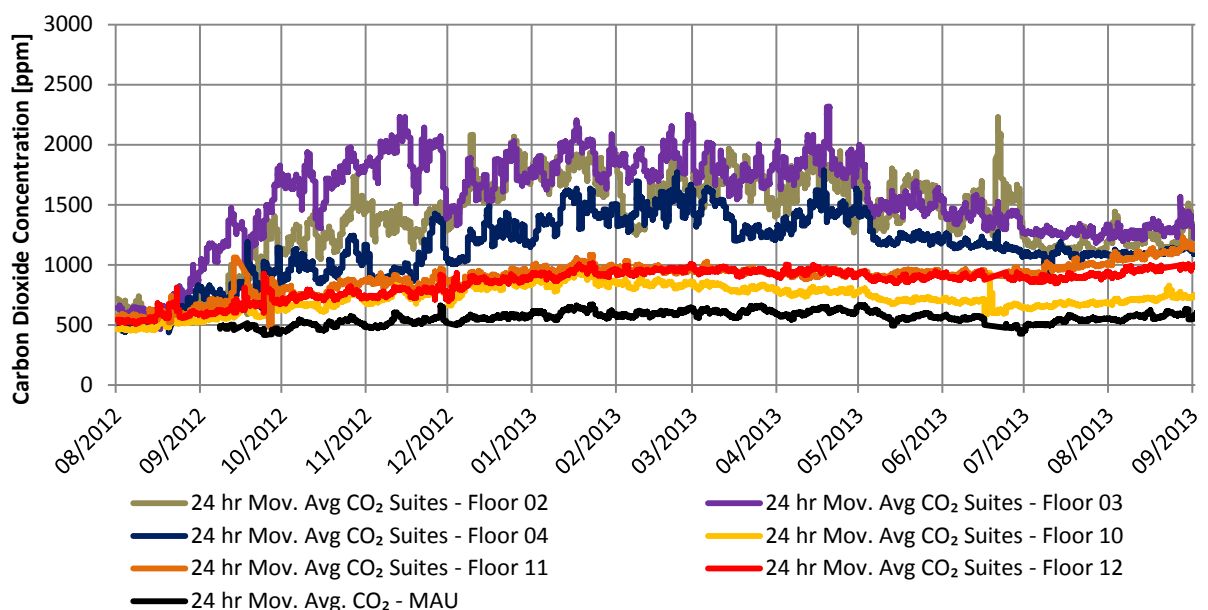


Figure 11: Chart showing average suite carbon dioxide concentrations by floor and carbon dioxide concentration of the intake air at the make-up air unit

The combination of the PFT testing and the carbon dioxide concentration monitoring indicates that the corridor pressurization ventilation system at this building is not effectively or efficiently ventilating the suites due to the combined interaction of building airtightness and the driving forces of airflow. Importantly, the poor performance of this system could likely have been predicted based on airflow theory.



5. CONCLUSIONS AND RECOMMENDATIONS

The theoretical interaction of building airtightness and the driving forces of airflow were evaluated for various climate conditions and compared with the measured results at a high-rise multi-unit residential case study building to provide context for the design of mechanical ventilation systems. At the case study building, the combined measurement of various different factors associated with airflows in buildings (including airflows themselves, indicators of indoor air quality, pressure difference, airtightness, and weather) allowed for the development of correlations such that conclusion could be drawn regarding the influence of each factor. This analysis generally concluded that the measured results corresponded well with the theory of airflow, and in particular illustrated that the complete combination of factors must be considered to design an effective and efficient mechanical ventilation system.

At the case study building, the inadequate consideration of all the relevant factors manifested in a poorly performing corridor pressurization based ventilation system which over-ventilates or under-ventilates the majority of suites in the building. Given that the case study building is archetypical of many mid- to high-rise multi-unit residential buildings, the performance of this system at the case study building is likely characteristic of the performance of this type of ventilation system.

The findings of this study clearly illustrate that stack effect and wind can frequently overwhelm pressure differences created by mechanical ventilation system resulting in unintended airflows into, out of, and within buildings. Furthermore, the airtightness of all building elements impact the distribution of pressure differences and consequently airflows. Overall, a holistic approach to building airflows should be taken when designing mechanical ventilation systems, including consideration of well understood airflow physics, to avoid designing poorly performing ventilation systems.

6. ACKNOWLEDGMENTS

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7. REFERENCES

- ASHRAE. 2010. ANSI/ASHRAE Standard 62.1-2010: Ventilation for Acceptable Indoor Air Quality. Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.
- ASHRAE. 2009. *ASHRAE Handbook – Fundamentals*. Atlanta: American Society of Heating, Refrigeration, and Air-Conditioning Engineers Inc.
- Cóstola, D., Blocken, B., & Hensen, J. (2009). *Overview of pressure coefficient data in building energy simulatoin and airflow network programs*. Building and Environment, Vol. 4, Issue 10, 2027-2036.
- D'Ottavio, T., Senum, G., and Dietz, R. 1988. Error Analysis Techniques for Perfluorocarbon Tracer Derived Multizone Ventilation Rates. *Building and Environment* Vol. 23, No. 3: 187-194.
- Hanam, B., and Finch, G. 2014. Evaluating the Energy Savings of High Performance Building Enclosure Retrofits. *2014 Canadian Conference on Building Science and Technology*. Oct 28
- Heiser, J., and Sullivan, T. 2002. *The Brookhaven National Laboratory Perfluorocarbon Tracer Technology: A Proven and Cost-Effective Method to Verify Integrity and Monitor Long-term Performance of Walls, Floors, Capps, and Cover Systems*. Upton: Brookhaven National Laboratory.
- Ricketts, L. 2014. *A Field Study of Airflow in a High-rise Multi-unit Residential Building*. MASc Thesis, Civil Engineering Dept., University of Waterloo.
- Ricketts, L. and Straube, J. 2014. *A Field Study of Airflow in Mid to High-Rise Multi-Unit Residential Buildings*. 2014 Canadian Conference on Building Science and Technology. Oct 28 – 30, 2014.
- Shaw, C, and Tamura, G. 1977. The Calculation of Air Infiltration Rates Caused by Wind and Stack Action for Tall Buildings. *ASHRAE Transactions* Vol 83, Part 2: 145-158.
- U.S. Department of Energy. (2013, July 16). Weather Data. Retrieved from EnergyPlus Energy Simulation Software: <http://apps1.eere.energy.gov/buildings/energyplus/>