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Pre-Retrofit Assessment of Thermal Comfort and Excess Moisture in Post-War Multi-Unit Residential Buildings in Toronto

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ABSTRACT

Energy retrofits provide an economically attractive solution to reduce the carbon footprint of existing buildings. However, indoor environmental quality and occupant comfort are often overlooked in the retrofit process. In this paper, we present the results of pre-retrofit monitoring of several multi-unit residential buildings built between 1965 and 1975 in Toronto, Canada. The temperature, relative humidity and mean radiant temperature were measured in over 70 units across seven social housing buildings currently undergoing an energy retrofit process. Occupant thermal comfort was estimated using both the Graphic Comfort Zone and Analytical methods outlined in ASHRAE Standard 55-2013. Internal vapor pressure excess during non-air conditioning periods was used to assess excess moisture in the suites. A major finding was that the units were uncomfortable over 50% of the time, with overheating being the main cause of discomfort. Location within a building (e.g., upper vs. lower floors) and building-specific effects showed little impact, although there was a weak seasonal correlation with more overheating in the summer. These findings are consistent with an occupant survey taken early in the project. There was no consistent evidence of excess moisture, although this may be due to the observed overheating in the units and the location of the monitoring equipment. The results were used to inform the energy retrofit design process and are currently being monitored to ascertain how the retrofits affect occupant comfort in these buildings.

INTRODUCTION

Constructing new more energy efficient buildings is an important step in addressing current energy concerns. However, with new construction accounting for just a few percent of the overall building stock and with the energy efficiency requirements increasing, the relative importance of our existing buildings will continue to grow. To meet future energy targets, it will be necessary to either re-build or retrofit existing buildings. From a capital and life-cycle economic cost perspective, retrofit options are preferred (Dong et al. 2005).

There are several papers in the literature which attempt to predict the impact of energy retrofits on indoor environmental quality (e.g. Hall et al. 2013; Ascione et al. 2015; Penna et al. 2015). A conclusion from these simulations is that retrofit measures can have a significant impact on comfort. However, in order to achieve the highest levels of energy performance without adversely impacting comfort it is necessary to implement measures which may not be economically favourable (Penna et al. 2015). Bohac et. al. (2011) investigated the inter-suite air exchange and found that air sealing and increasing ventilation could significantly reduce second-hand smoke transmission. Noris et al. (2013)

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performed a broader investigation of 16 apartments serving low-income populations. The authors studied the impact of an extensive package of retrofit measures and observed a general improvement post-retrofit in thermal comfort, bathroom humidity, CO_2, VOC and particle concentrations. The current study advances our understanding of retrofit impacts by monitoring a significantly larger population for a considerably longer period.

The current study seeks to evaluate the impact of energy retrofits on occupant health and comfort by measuring indoor environmental quality parameters both pre- and post-retrofit. The study population comprises of over 70 units across seven social housing buildings in Toronto, Canada. Each suite will be monitored for a total of two years with the energy retrofits occurring in the middle of the monitoring period. This paper presents the results of the first nine months of data in the context of two parameters: thermal comfort and vapor pressure excess. Data obtained during this period was used to establish pre-retrofit baseline conditions and inform the retrofit process.

A summary of the site characteristics is provided in Table 1. All seven buildings were built between 1965 and 1974 and range from 4 to 19 floors. The building occupancy type for all buildings was residential class R2 (ICC 2015), but the primary family type varied between buildings. Sites A, B and D were largely senior residences, while sites C and E were low occupancy bachelor units and sites F and G were family residences. Heating is provided to all of the study suites via hydronic baseboard heaters. Fresh air is supplied to the building corridors through air-handling units equipped with supplemental heating. Many of these units were observed to be running at low speeds, supplying less fresh air than required. The buildings do not have central cooling, however, 30-40% of units have window air-conditioning units installed. The number of suites involved in the study has declined since the start of the monitoring due to participants withdrawing for various reasons. To keep the study population over 70 suites, we have added additional suites.

Table 1. Site Characteristics

Site	Year Built	# of Suites at Start	# of Suites at 9 mo.	# Floors	Floor Area (sq.ft.)	% Monitored	Family Type
A	1972	10	11	4	113,580	6	Senior
B	1972	10	9	4	97,920	4	Senior
C	1965	14	14	7	126,540	6	Bachelor
D	1965	4	3	7	35,960	7	Senior
E	1965	11	13	11	116,820	6	Bachelor
F	1974	11	11	19	148,485	7	Family
G	1974	13	13	18	206,928	6	Family

METHODS

A long-term monitoring package was installed in each suite. The packages consisted of the equipment listed in Table 2 as well as a CO_2 sensor. An Onset HOBO U12-012 data logger records the data at 15-minute intervals. An approximate measure of mean radian temperature (MRT) was obtained using an Onset TMCx-HD temperature probe inserted behind a small black half-sphere pointing towards the occupied space. The result of this measurement is not an absolute measure of MRT, but it allows for a reasonable estimate of thermal comfort and facilitates pre- and post-retrofit comparisons. The packages were installed in similar locations across the different suites. None of the packages were installed in bathrooms and kitchens were avoided where possible.

Table 2. Summary of Instrumentation

Measurement	Manufacturer	Model	Accuracy
Temperature	Onset	HOBO U12-012	±0.35 °C
Relative Humidity	Onset	HOBO U12-012	± 2.5 %
Mean Radiant Temperature	Onset	TMCx-HD	±0.25 °C

Occupant thermal comfort was calculated first using the Graphic Comfort Zone Model outlined in ASHRAE Standard 55-2013 (ASHRAE 2013a). This method relies on knowledge of several parameters that were not directly

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measured such as activity level, clothing and air velocity. All assumptions are provided in Table 3. The method is restricted to occupant activity levels between 1 and 1.3 met, clothing insulation values between 0.5 and 1.0 clo and humidity ratios at or below 0.012 $kg_{H2O}/kg_{dry\ air}$. For further details regarding this method, refer to ASHRAE Standard 55 section 5.3.1. Limitations of this approach include uncertainties in metabolic rate and heat production as well as the assumption that the parameters are constant. There are several alternative methods used to evaluate occupant thermal comfort, such as the adaptive comfort model, which consider an occupant's response to thermal discomfort. In this study we've applied the Graphic Comfort Zone method twice to determine an upper and lower bound to the predicted thermal comfort. The lower bound was established by applying the graphic method with a default clothing value of 0.75 clo, which corresponds to sweat pants and a long-sleeve sweatshirt. An upper bound was established by applying the model with a clothing value between 0.5 and 1.0 in such a way as to maximize the predicted thermal comfort. For example, the clothing level was reduced when the conditions were predicted to be too hot. Thermal comfort was also calculated using the analytical method described in ASHRAE Standard 55 Section 5.3.2.

Table 3. Summary of Thermal Comfort Input Parameters

Parameter	Value	Units	Notes
Activity	1.0	met	Equivalent to someone who is resting or seated
Air Velocity	0.15	m/s	Equivalent to no perceived draft
Clothing (Lower)	0.75	clo	Sweat pants, long-sleeve sweatshirt
Clothing (Upper)	0.5 – 1.0	clo	Full range of clo values for the ASHRAE Graphic Comfort Zone Method

Internal Vapor Pressure Excess (VPE or Δp) is a single measure that can be used to assess the relative moisture of an indoor environment compared to its exterior environment. VPE is calculated using Equation 1.

$$VPE = p_i - p_e \tag{1}$$

where p_i is the interior vapor pressure, and p_e is the exterior vapor pressure. VPE can be used to compare the moisture balance of separate indoor environments as was done by Glass and TenWolde (2009), Francisco and Rose (2010) and others. VPE results are generally restricted to heating periods, where the outdoor temperature is less than 20 ℃ (68 ℉) to control against artificial changes in vapor pressure caused by mechanical cooling equipment. In heating climates, VPE tends to follow a general pattern when plotted against the exterior temperature (ISO 2012). The pattern comprises of two components separated by an inflection point around 0 ℃ (32 ℉). At exterior temperatures below the inflection point, VPE is a constant positive value. When the exterior temperature exceeds the inflection point, VPE decreases linearly towards an intercept around 20 ℃ (68 ℉) Francisco and Rose (2010) corroborated this pattern. The results of this study also follow the established pattern with the exception of an inflection point consistently above 0 ℃ (32 ℉). In order to obtain the moisture balance for each suite, the inflection point was determined for each suite using a moving average. The averaging period was 48 measurements (12-hour time span) and the inflection criterion was a slope less than -1 Pa/min. The moisture balance was then calculated by averaging the VPE from the lowest exterior temperature up to the inflection point. The averaging period and slope constraint were the result of a trial and error approach and visual inspection of the results. This method is suitable for comparing differences between suites and buildings, but is not intended as an estimate of the absolute interior moisture conditions of the space.

RESULTS

The lower (a) and upper (b) bounds of thermal comfort are shown at the individual suite level in Figure 1. The buildings are separated by vertical black bars.

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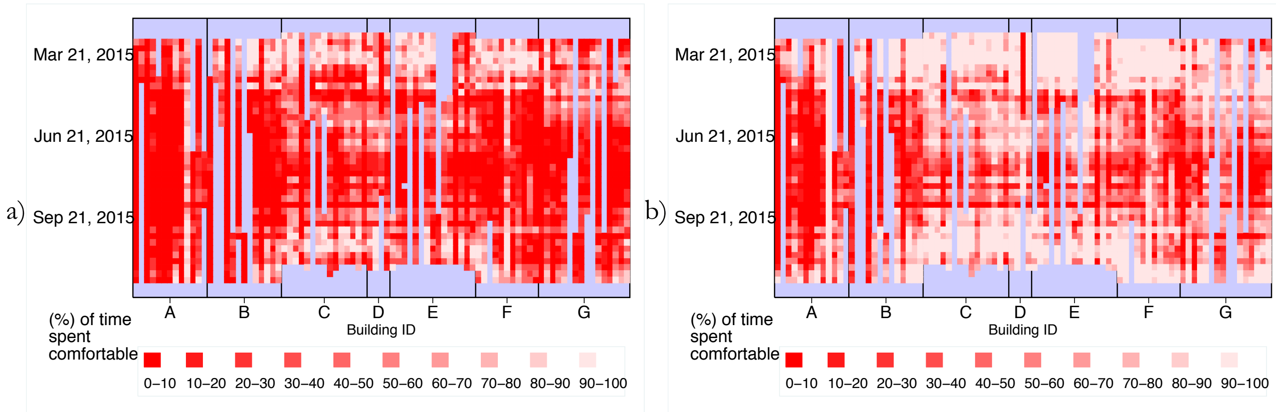

Figure 1 (a) lower bound of occupant thermal comfort in % of time spent comfortable and (b) upper bound of occupant thermal comfort in % of time spent comfortable. Each square represents an average value in a unit for a week. Gaps in the heat map, where the light blue background is visible, are due to participants withdrawing from the study or entering into the study later that the original date.

A closer look at the range of predicted thermal comfort values is shown for site G in Figure 2. The results are ordered such that the height of the suites in the building increases left to right. The dot shows the percentage of time spent comfortable based on the analytical (PMV) method. The upper and lower tails correspond to the upper and lower estimates using the Graphic Comfort Zone method respectively. The average predicted thermal comfort according to the analytical (PMV) method was 45%, but ranged from 5% to 86% comfortable. In less than 10% of the suites, the estimated thermal comfort predicted using the PMV method was lower than the lower bound of the graphic thermal comfort method. This was due to differences between how the methods handle the input parameters and rounding near the boundaries of the graphic method.

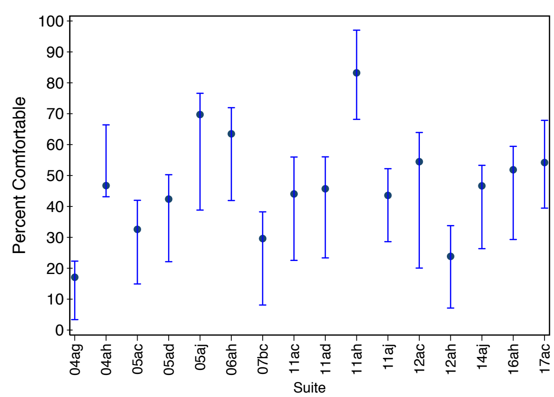

Figure 2 The range of predicted comfort for building G for the first 9 months of pre-retrofit data. The first two digits of the suite code are the floor of the suite. The lower and upper bounds are based on the ASRHAE Graphic Comfort Zone Model. The lower bound assumes that the clothing level is fixed at 0.75 clo, while the upper bound assumes the clothing level can be anywhere between 0.5 and 1.0 clo. The dot is based on a |PMV| < 0.5 using the method outlined in Appendix D of ASHRAE Standard 55.

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In order to understand both the cause and severity of discomfort, a heat map of the suite indoor air temperatures is shown in Figure 3. Figure 3 suggests that overheating is the most common reason for discomfort with many suites exceeding 25 °C (77 °F) all or most of the time.

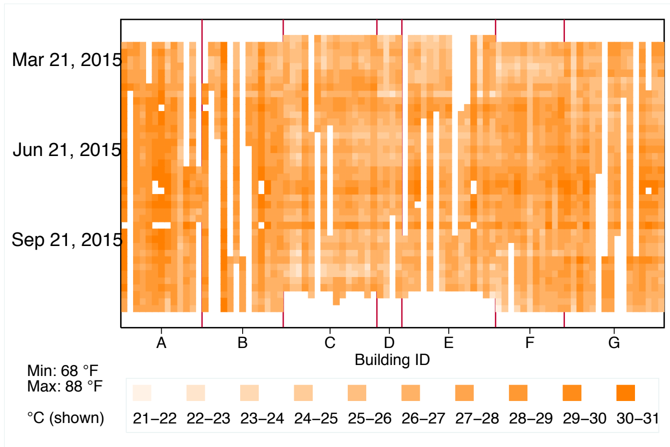

Figure 3 A heat map of the indoor air temperature for all suites in the study, separated by building. Each block of the heat map represents the average value over a week of monitoring. Gaps are present due to participants withdrawing from the study or replacement suites who entered after the beginning of the monitoring period.

The internal vapor pressure excess for the suites in each building is presented in Figure 4. We have categorized the results based on the indoor climate classes described in ISO Standard 13788, as was done by Francisco and Rose (2010). The interior climate class definitions are shown graphically in Figure 4 with dashed red lines. Class 1 and Class 2 refer to storage areas and offices spaces respectively. While Classes 3 and 4 refer to low and high occupancy dwellings. Class 5 is for high use spaces like kitchens. The moisture balance values obtained during this study are lower than would be predicted by the occupancy class definitions in ISO 13788, with most suites falling into classes 1 or 2. The median moisture balance across all suites was 326 Pa. The max was 1473 Pa and the minimum was -25 Pa.

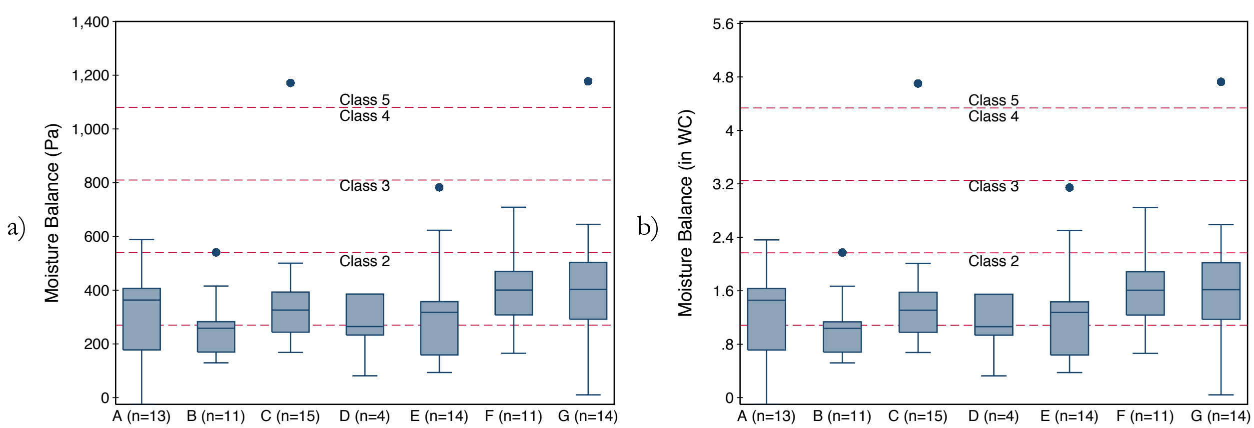

Figure 4 Moisture balance results for all 7 buildings a) Pa, b) inWC. The moisture balance was determined as the average VPE at all exterior temperatures less than the exterior temperature at inflection. The red dash lines indicate the ISO Standard 13788 indoor climate class. The box plot shows the building median (line), the upper and lower quartiles (upper/lower boundaries of the box), and 1.5· the interquartile range. Dots represent single suite outliers.

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DISCUSSION

This section first discusses the collected data and then describes the implications for the retrofits. Data from the first nine months of pre-retrofit data suggests low levels of thermal comfort in the suites, with uncomfortable conditions predicted roughly half the time. The primary cause of thermal discomfort was excess heat rather than insufficient heat or excess moisture. In some suites, the discomfort was severe with average weekly indoor temperatures exceeding 30 °C (86 °F) or more. Thermal comfort varied seasonally with the (relatively) highest comfort observed in the spring and the lowest comfort in the summer. While elevated thermal discomfort during the summer is consistent with the lack of central of cooling and the use of operable windows/doors to control interior conditions, the uncomfortable conditions observed during the spring are due to the heating system overheating the units. Residents did not have control over the heating set point of their suite. Thermal discomfort was most pronounced in building A. The reasons are unclear, but may be the result of the building specific features including system set point temperatures and the condition of the heating equipment.

Previous investigations of the indoor environmental quality of multi-unit residential buildings have observed correlations between IEQ and height (e.g. Montgomery 2015) due to unbalanced HVAC systems. No relationships with height were observed for either thermal comfort or VPE during the first nine months of data collection. The unknown and inconsistent use of and access to suite level air conditioning units may have contributed to the lack of relationships with height or other parameters.

All of the study buildings exhibited moisture balances lower than anticipated by the interior climate class definitions specified in ISO Standard 13788. This result is consistent with the general observation that windows and balcony doors remained open to help cool the units during the monitoring period. According to the definition of VPE, natural ventilation will tend to decrease the moisture balance since it decreases the difference between interior and exterior vapor pressures. Overheating of the suites may also have contributed to drying out the suites and decreasing the moisture balance.

There are several limitations affecting the current study. The first limitation is the lack of precise input data for the thermal comfort models. This includes the use of a surrogate MRT measurement and the reliance on assumptions for unmeasured parameters: clothing, activity and air speed. The result of uncertainty in the input parameters is a large range in predicted thermal comfort results, however the overall finding of discomfort because of overheating agrees with the results of an occupant survey conducted at the beginning of study. The second limitation was the lack of air-conditioner usage data, which may have masked height relationships and led to unusually low moisture balances. This may also have impacted the moisture balance results since they were determined using all data points where the outdoor temperature less than 20 °C (68 °F) and it is possible that residents with access to air-conditioning choose to run their air-conditioners when the outdoor temperature met this criterion due to overheating. Although this does not guarantee that all periods of air-conditioner use are excluded, when data from the summer is excluded the result is a slightly smaller range of moisture balances and a slightly higher median moisture balance, which is consistent with air-conditioner use in the summer. Despite these limitations, the data obtained during the pre-retrofit period has provided a useful basis for comparison during the post-retrofit period. Significantly, this data, which is usually not available, has also allowed key decision makers to recognize and prioritize measures which can improve thermal comfort as opposed to focusing purely on energy conservation and economic return.

Impact on Retrofits

A variety of retrofit strategies are needed to address the thermal comfort problems that have been identified through the monitoring data. The existing hydronic radiators across the seven buildings have hot water flowing at constant rates with no in-suite controls. Along with oversized boilers that cycle often and consume a significant amount of natural gas, the current building heating systems provide an excess amount of heat. To improve the thermal comfort during the heating season and reduce space heating energy consumption, new hydronic radiators and in-suite controls

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are proposed. Additional measures targeting the mechanical systems such as optimizing the existing heating controls, separating the space heating and domestic hot water loops, and replacing the existing heating boilers with smaller and more efficient units have been identified in the design process. These measures are intended to better align the heating output from the mechanical systems with the building heating demand.

During the summer, measures to reduce solar heat gain and cooling strategies are needed to address the low thermal comfort found across the suites. Ideally, providing cooling at the suite level will result in the greatest thermal comfort improvement. However, installing a suite based cooling system can be cost-prohibitive (from both capital and energy use perspectives) and will require extensive air sealing. When examining the monitoring data, thermal comfort was not significantly affected by the presence of window air-conditioning units. Although this trend could be a result of how often the residents use their air conditioners, it is more likely an indication of how effective these units are in operation. Since many residents install their own air-conditioning units, air leakage paths surrounding the window air conditioners and other performance failures are common. This not only results in high electrical building consumption, but also does not alleviate the thermal comfort problem during the summer.

One alternative to suite based cooling is to provide cooling through the central makeup fresh air supply. Consolidating the number of existing makeup air units to fewer standalone rooftop units and adding a cooling coil will result in cold, conditioned air being supplied to the building corridors. Provisions have to be made to ensure this air is not obstructed from entering the suites. Improvements to the makeup air systems will also provide an opportunity to bring fresh air supply rates up to Ontario Building Code and ASHRAE Standard 62.1 ventilation requirements. Additional planned approaches for improving the quality of ventilation air include routine duct cleaning and air sealing.

The low VPE observed across these buildings could be a result of balcony door and window opening throughout the year. During the survey, 22% of occupants reported opening windows during the winter to alleviate overheating. By implementing measures that reduce the amount of time units overheat, the VPE could increase. To ensure that excess moisture is removed quickly from the indoor environment, particularly in the bathrooms, the central building exhaust ducts are planned to be cleaned and air sealed to allow the fans to work at their intended design levels. Similarly to the fresh air supply ducting, these measures will help bring the exhaust airflow up to building code requirements.

CONCLUSION

Preliminary data obtained prior to performing energy retrofits suggests that there is room to improve the thermal comfort of occupants. Conditions in the suites were determined to be uncomfortable approximately 50% of the time. The main cause of thermal discomfort was overheating. Calculated moisture balances were low and it was hypothesized that natural ventilation and overheating were the primary contributors. Neither thermal comfort nor moisture balance showed significant correlation with height or any other building specific characteristics examined. A discussion of the potential retrofit options suggests that there is the potential to both improve and degrade indoor environmental quality.

ACKNOWLEDGMENTS

The authors would like to acknowledge our community housing partner and the many participants of this ongoing study.

NOMENCLATURE

VPE = vapor pressure excess (Pa)
p = pressure (Pa)

Subscripts

i = indoor
e = exterior

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