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Using Dynamic Glazing to Eliminate Mechanical Cooling in Multi-family Highrise Buildings

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Abstract**—**Multifamily residential buildings are increasingly being built with large glazed areas to provide tenants with greater daylight and outdoor views. However, traditional double-glazed window assemblies can lead to significant thermal discomfort from high radiant temperatures as well as increased cooling energy use to address solar gains. Dynamic glazing provides an effective solution by actively controlling solar transmission to maintain indoor thermal comfort, without compromising the visual connection to outdoors. This study uses thermal simulations across three Canadian cities (Toronto, Vancouver and Montreal) to verify if dynamic glazing along with operable windows and ceiling fans can maintain the indoor operative temperature of a prototype southwest facing high-rise apartment unit within the ASHRAE 55 adaptive comfort range for a majority of the year, without any mechanical cooling. Since this study proposes the use of natural ventilation for cooling and the typical building life cycle is 30-40 years, the typical weather files have been modified based on accepted global warming projections for increased air temperatures by 2050. Results for the prototype apartment confirm that thermal discomfort with dynamic glazing occurs only for less than 0.7% of the year. However, in the baseline scenario with low-E glass there are up to 7% annual hours of discomfort despite natural ventilation with operable windows and improved air movement with ceiling fans.

Keywords**—**Electrochromic, operable windows, thermal comfort, natural ventilation, adaptive comfort.

I. Introduction

MULTIFAMILY residential buildings are increasingly favoring designs with large glazed areas to provide tenants with greater daylight and outdoor views. While the health benefits of natural light and views are now well-established and these are desirable design outcomes, a consequence of highly glazed buildings fitted with traditional double glazed glass window assemblies is often thermal discomfort from high radiant temperatures and an increase in cooling energy use due to high space solar gains. Dynamic glazing includes a range of adaptive glazing technologies that can help balance energy use and indoor comfort without compromising the visual connection to outdoors.

This study uses simulations to verify if dynamic glazing, along with operable windows and ceiling fans can maintain the indoor operative temperature of a southwest facing apartment unit within the ASHRAE 55 adaptive comfort range for a majority of the year, without any mechanical cooling. The selected building prototype model is meant to reflect a high-rise residential condominium with design inputs typical of the Canadian market. In doing so it is our intent that no other design changes other than the ones investigated – use of dynamic glass, ceiling fans, operable windows and elimination of a cooling system – would be required for a designer or developer to make use of the findings of this study. Results have been presented for three Canadian cities - Vancouver, Toronto & Montreal. A reference baseline scenario has been created with a traditional dual pane high-performance glazing product and manually controlled fabric interior shades.

This study draws on the fact that people who live or work in naturally ventilated buildings, where they are able to open windows, become used to experiencing inherently more variable indoor thermal conditions that reflect local patterns of daily and seasonal climate changes. Their thermal perceptions – both their preferences as well as their tolerances – are likely to extend over a wider range of temperatures [1] than typically deemed acceptable in air-conditioned buildings. This is the basis for the adaptive comfort model, which states that the temperature at which people are most comfortable is related to the temperatures they are used to experience and is a result of both behavioral and psychological adaptation [2], [3].

An important premise of the adaptive comfort model is that the building occupant is no longer simply a passive recipient of the thermal environment as given, as in the case of a climate chamber experimental subject, but instead is an active agent interacting with all levels of the person-environment system via feedback loops [3]. Dynamic glazing allows an occupant to control their visual and thermal environment to a much higher degree than regular glazing and provide behavior feedback that is central to the adaptive comfort model.

By eliminating mechanical cooling equipment, dynamic glazing coupled with natural ventilation can lower energy use, helping buildings become Net Zero Energy Ready (NZER). A NZER building minimizes energy consumption such that onsite renewables or energy sourced from a clean grid can then be used to reach net-zero energy (NZE) status [4]. In 2016 the Pan-Canadian Framework on Clean Growth and Climate Change (PCF) committed to a NZER model building code by 2030 [4]. British Columbia has committed to a NZE ready standard for new buildings by 2032 [5]. A similar approach is being adopted by cities all over North America in an effort to reduce emissions and combat climate change.

Since this study is recommending only the use of natural ventilation for cooling and the typical building life cycle is 30-40 years, the annual thermal comfort simulations have been performed with weather files modified using global warming projections for increased air temperatures by 2050.

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II. Overview of Key Concepts

A. Adaptive Comfort in Naturally Ventilated Spaces

The deterministic understanding of thermal comfort is driven exclusively by the thermodynamics of heat exchange between the body and its immediate thermal environment. But over the last several decades there has been widespread recognition that a person's thermal history and past adaptation level also influence whether indoor climatic conditions will be deemed comfortable or not [6]. This contextual view of comfort is referred to as the adaptive comfort model (ACM).

Field experiments have shown that occupants in naturally conditioned spaces with operable windows have a different subjective notion of comfort because of different thermal experiences, availability of control, and resulting shifts in occupant expectations [7]. The operation of windows in a naturally ventilated building influences both local temperature and air movement [2]. Natural ventilation brings about comfort by air movement on the skin and by air changes that displace the warm stale air in the room whenever the air outside is cooler than the air inside.

In 2004 ASHRAE ratified the first global adaptive comfort standard based on the statistical evaluation of 21,000 complete sets of objective indoor climatic measurements and their subjective evaluations by the building occupants who were exposed to those conditions [3]. Since ASHRAE Standard 55-2004 was published there has been an escalation in adaptive comfort field research activity around the world [1].

ASHRAE/ANSI Standard 55 [7] recognizes and permits the use of the ACM to define acceptable thermal conditions for occupant-controlled naturally conditioned spaces which have no mechanical cooling. The ACM accounts for local thermal discomfort, clothing insulation, metabolic rate, humidity, and air speed. So, it is not required that they are separately evaluated when using this model [7].

B. Dynamic Glazing

Dynamic glazing includes a range of adaptive glazing technologies that can help balance energy use and indoor comfort without compromising the visual connection to outdoors. Such glazing products improve energy efficiency and comfort by modulating the transmittance of solar energy and light. This type of glazing is typically referred to as "smart" or "intelligent" glazing and is based on chromogenic materials, with electrochromic (EC) materials currently being the most widely studied and commercially used for exterior window applications [8]. EC windows allow solar transmission to be changed in a controlled and reversible manner using low voltage electric current.

An EC glazing unit typically consists of a 90% argon filled insulated glazing unit (IGU) with a 6 mm tempered clear outer lite with the EC coating on surface 2 and a 6 mm tempered clear inner lite. The specific IGU product used in this study has four tint states that are automatically controlled by an algorithm which accounts for building geometry, indoor furniture layout, location specific sun path analysis and on-site weather variations. By default, the control algorithm automatically selects the appropriate tint state for a window based on three functional modules in order of priority [9].

- Direct Glare Control: Ensure there is no direct sun penetration within a specified interior occupancy zone or beyond a specified indoor distance from façade. This includes both direct and indirect specular glare.
- Heat Load Control: When glare is not present select the appropriate EC tint state that will keep solar heat gain below a specified threshold, while also allowing for adequate natural light.
- Weather Control: Use site-specific real time weather inputs from a roof mounted photosensor to determine the appropriate tint state under overcast conditions.

If desired, the occupant can override the automated window tint state selection, either via a software app installed on their phone or using a touchscreen wall switch.

C. Design Analysis for Climate Change

Various future trajectories of greenhouse gas (GHG) emissions are possible and depend directly on global political initiatives and socio-economic changes that will occur over the coming years. Representative Concentration Pathways (RCPs) describe potential 21st century scenarios of GHG emissions, atmospheric GHG concentrations, air pollutant emissions, and land use [10]. These RCPs are used for making projections and are based on the factors that drive anthropogenic GHG emissions: population size, economic activity, lifestyle, energy use, land use patterns, technology adoption, and climate policy.

It is critical for building designers and engineers to understand how buildings constructed today might perform 30-40 years in future when temperatures are expected to increase on average by 3-5 °C. This is especially pertinent for buildings that are designed for active use of natural ventilation without mechanical cooling. To enable this type of future performance analysis it is now possible to generate future weather data, with a "morphing" technique [11] that transforms historical time series weather data to match projected changes in the monthly averages of climatic variables such as air temperature and precipitation.

III. Methods

A. Study Overview

A high-rise condominium building with design inputs typical of the Canadian market has been selected for thermal comfort simulations across three cities representative of climate zones 4 (Vancouver), 5 (Toronto) & 6 (Montreal). For the sake of brevity, results from only the south-west corner unit have been analyzed and discussed in this study. The south west corner unit was identified as having the highest annual direct solar radiation exposure and greatest potential for thermal discomfort. In addition, the typical floor is modelled at 40 meters above ground level to represent the scenario of a high-rise unit which is less impacted by shading from adjacent buildings and receives year-round direct solar radiation.

This typical floor has been simulated for each city using future weather files adjusted for climate change projections between 2030 and 2050. Fig. 1 shows a single typical floor with a mix of 1 and 2 bed units.

Keeping all other design parameters constant, two glazing scenarios have been evaluated:
1) EC glazing
2) Low-E glazing with fabric interior shades (manual)

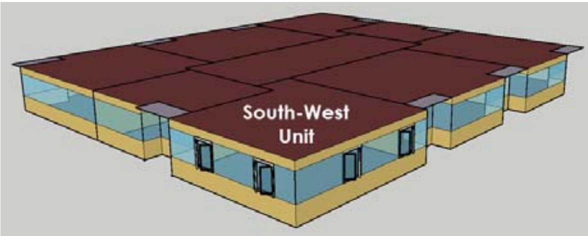

Fig. 1 Energy model of typical floor

B. Building Model Description

Several inputs to the building energy model have an impact on the thermal loads within each suite. Key inputs include:

- Suites are all either one or two bedrooms. The average suite size is 86.16 m^2. The typical floor to floor height is 2.90 m.
- Suites are modelled as single thermal zones.
- Infiltration rates are set to 0.25 L/s/m^2, following modelling guidance in the National Energy Code for Buildings (NECB) [12]
- In-suite lighting and equipment power densities are both set to 5 W/m^2, as per NECB modelling rules.
- Occupants are assumed to be 1 person for every suite, plus one additional person for every bedroom.
- Load schedules for occupancy, and lighting and equipment power all follow the NECB schedule set G, representing residential space types.
- No heat transfer was assumed to the floors above and below the typical floor as it is expected that these areas would maintain the same or similar heating and cooling setpoints.
- Opaque portions of the building envelope are modelled as spandrel panel glazing. These areas assume 3 inches of semi rigid insulation in the spandrel back pan, as well as 3 inches of batt or spray foam insulation within a steel stud backup wall. An effective R value of 1.67 m^2K/W (R-9.5) represents this assembly when accounting for thermal bridging.
- A Window-to-wall ratio (WWR) of 50% vision glazing was chosen for this study in recognition that many developers express a desire for higher WWR.
- No exterior fixed shading has been modelled.
- 30% of the available window area is assumed to be operable.
- Space heating is served by in-suite fan coil units.
- Natural ventilation through operable windows is the only mode of space cooling. Ceiling fans are modeled to increase indoor air movement and improve comfort.
- Suite ventilation is served by an in-suite energy recovery ventilator (ERV) with a 65% sensible effectiveness.
- Ventilation is provided to the suite at a constant low speed of 23.6 L/s, with the ability to increase the speed up to 35.4 L/s via use of a bathroom wall mounted timer switch. A time weighted average of 26.0 L/s was modelled for each suite, assuming 80% of the time would be spent on low speed and 20% on high speed.

C. Simulation Model Setup

EnergyPlus v9.1 (E+) was used to generate the annual thermal simulations. The Energy Management System (EMS) feature [13] within E+ was used to control the multi-tint dynamic glazing, operate the windows & ceiling fans, and compute the annual hours of adaptive thermal comfort.

The EMS feature in E+ has been developed to simulate many novel control algorithms that are not possible with the previous generation of building simulation programs [14]. A language called EnergyPlus Runtime Language (Erl) is used to write programs describing the control algorithm, which are then interpreted by E+ at run-time. The EMS feature offers a “sensor” object that reuses standard E+ output variables that can be queried at different points in the simulation cycle such as before or after zone loads are computed at each timestep. A counterpart EMS actuator object acts as the conduit by which Erl programs control and override the behavior of EnergyPlus components such as surface constructions, thermostat setpoints, internal shades etc. [14].

E+ has an actuator available that can be used for modeling dynamic technologies such as EC windows [13]. This actuator is called - Surface - and has a control type - Construction State - which allows EMS to assign and override any default construction assigned to the window, based on user defined instructions contained in an EMS program [9], [13].

The operable windows have been modelled using the ZoneVentilation:WindandStackOpenArea object. Using this object, the natural ventilation flow rate can be controlled by an opening area fraction schedule applied to the total operable area in each window. 30% of the window area on the south and west façades of the selected unit have been considered operable. It should be noted that the ventilation is solely wind driven and there is no stack effect in this situation since one only floor has been modeled.

The ceiling fan has been modelled as a single speed fan added to the zone as a unit-heater that has no heating capacity. This was necessary since E+ does not have a way of adding a fan directly to a thermal zone unless it is part of some HVAC equipment. The selected fan model has an actual diameter of 1.5 meters with a maximum rated air speed of 1.6 m/s, drawing 30 Watts. Since the air speed experienced by an occupant in the room is likely to be affected by the height of the fan blades and the distance from the fan location, the maximum fan induced air speed has been lowered to 1.2 m/s for the purpose of this study.

Since most weather stations are located in an open field, the Terrain field in the Building object has been changed to City. E+ uses this input to account for the roughness characteristics of the surrounding terrain around a high rise in a typical city center, and appropriately modifies the weather file wind speed when calculating the wind driven ventilation rates.

D. Window and Ceiling Fan Operations

The natural ventilation program is set up to assess the possibility of opening windows and/or turn on the ceiling fan anytime of the day or night, only if the interior zone air temperature is > 24℃ and outdoor conditions are appropriate. 24 ℃ is a typical thermostat setpoint that would activate mechanical cooling in the residential unit if it were available. The ceiling fan is switched on first before the windows are opened.

Fig. 2 describes the window operation algorithm which mimics the behavior of occupants who typical control the window opening area based on outdoor air temperature (OAT) and wind speed. By default, the windows are closed if OAT < 22 ℃, which is also the zone heating setpoint. An exception however is allowed if the OAT is between 20 and 22 ℃ and the zone air temperature is > 24 ℃. In that scenario the window opening area is assigned a multiplier of only 0.1, to simulate a situation where the windows are slightly opened to provide some cooling to lower the room air temperature without simultaneously activating the mechanical heating system.

```
IF (OutdoorAirTemp - ZoneAirTemp > 1°C)
    SET Window = 100% closed
ELSEIF (20 °C <= OutdoorAirTemp <= 22 °C)
    SET Window = 10% open (slightly cracked open)
ELSEIF (OAT > 22 °C) & (WindSpeed <= 3 m/s)
    SET Window = 100% open
ELSEIF (OAT > 22 °C) & (3 m/s < WindSpeed <= 6 m/s)
    SET Window = 67% open
ELSEIF (OAT > 22 °C) & (WindSpeed > 6)
    SET Window = 33% open
ELSE
    SET Window = 100% closed
```

Fig. 2 Window operation algorithm

When the windows are open, the ceiling fan is assumed to be on only if the wind speed is less than the fan driven air speed of 1.2 m/s. Else the fan is kept off. When the windows are fully closed the fans are set to turn on if zone air temperature rises above 24 ℃. Fig. 3 describes the ceiling fan operation.

```
IF (WindowOpen = True) & (WindSpeed <= 1.2 m/s)
    SET Fan On
ELSEIF (WindowOpen = True) & (WindSpeed > 1.2m/s)
    SET Fan Off
ELSEIF (WindowOpen = False)
    SET Fan On
ELSE
    SET Fan Off
```

Fig. 3 Ceiling fan operation algorithm

E. Fenestration Model

The Full Spectral Model is the preferred method of modeling windows in E+ because it accounts for the wavelength-by-wavelength optical interactions between glass layers [15]. Spectral glazing files were exported from LBL Window 7.7 [16]. Table I shows properties for each tint state of the EC window and for the traditional low-E baseline. The EC IGU has a low-E coating on surface 4 to match the U-value preferred in Canadian cities. Thermally broken aluminium frames provide an assembly U-value of 2 W/m^2-K.

As is common in most apartments, the baseline glazing scenario has been provided with 3% openness factor interior fabric shades that have a solar transmission and reflectance of 6% and 47% respectively. The shades are modelled as fully down whenever incident solar on a window is > 400 Watts/m^2 and are otherwise fully up, with no intermediate position.

TABLE I
GLAZING PERFORMANCE

Glazing	SHGC	Tvis	Center of Glass U Value
EC Tint 1	0.34	0.46	1.322 W/m^2-K
EC Tint 2	0.17	0.20	
EC Tint 3	0.10	0.06	
EC Tint 4	0.08	0.01	
Low-E Baseline	0.35	0.68	1.366 W/m^2-K

F. ASHRAE Standard 55 Compliance

ASHRAE Standard 55 utilizes the ACM to define acceptable thermal conditions for occupant-controlled naturally conditioned spaces which have no mechanical cooling [7]. It is permissible to use mechanical ventilation with unconditioned air and to have a heating system installed.

The input variable in the ACM is the prevailing mean OAT $\overline{t_{pma(out)}}$. It represents the broader external climatic environment to which building occupants have become physiologically, behaviorally, and psychologically adapted. At its simplest $\overline{t_{pma(out)}}$ can be approximated by the monthly mean air temperature from the most representative local meteorological station available. When used in conjunction with dynamic thermal simulation software, the preferred expression for $\overline{t_{pma(out)}}$ is an exponentially weighted, running mean of a sequence of mean daily outdoor temperatures prior to the day in question. Days in the more remote past have less influence on the building occupants' comfort temperature than more recent days, and this can be reflected by attaching exponentially decaying weights to the sequence of mean daily outdoor [17].

This study uses the exponentially weighted running mean method with a range of seven days prior to the day in question. If $\overline{t_{pma(out)}}$ is less than 10 ℃ or greater than 33.5 ℃, the ACM is not applicable.

The ACM uses operative temperature t_o to assess comfort for a given value of $\overline{t_{pma(out)}}$. Operative temperature is calculated as the average of the indoor air dry-bulb temperature and the mean radiant temperature of zone inside surfaces.

ASHRAE 55 provides (1) and (2) that define compliance with the ACM as long as t_o is within the upper and lower 80% acceptability limits. The 80% acceptability limits imply that at least 80% of occupants will be satisfied with indoor operative temperatures within this range.

$$Upper\ Limit\ (°C) = 0.31 * \overline{\boldsymbol{t_{pma(out)}}} + 21.3 \quad (1)$$

$$Lower\ Limit\ (°C) = 0.31 * \overline{\boldsymbol{t_{pma(out)}}} + 14.3 \quad (2)$$

The cooling effect of elevated air speeds at relatively warm temperatures is recognized by ASHRAE 55 [17]. For $\boldsymbol{t_o}$ > 25 °C, and air speed > 0.3 m/s, it is permitted to increase the upper acceptability temperature limit in (1). The highest adjustment is for an air speed >= 1.2 m/s, wherein the upper limit can be increased by 2.2 °C, as shown in (3)

$$Upper\ Limit\ (°C) = 0.31 * \overline{\boldsymbol{t_{pma(out)}}} + 21.3 + 2.2 \quad (3)$$

During the annual simulation, whenever the windows are closed, if the ceiling fan is running it provides a constant air speed of 1.2 m/s. The fan is also modelled to be running when the windows are open but the outside wind velocity normal to the windows is < 1.2 m/s. This operational procedure between fan and window ensures that the air speed in the room is >= 1.2 m/s. As a result, during the simulation whenever $\boldsymbol{t_o}$ was greater than 25 °C, and either the fan was running or the window was open, the ASHRAE 55 upper 80% acceptability limit was increased by 2.2 °C as shown in (3).

G. Weather File Modifications for Future Projections

TMY weather files are based on historical data and are inaccurate for estimating the future performance of buildings, especially those with lifetimes exceeding 30 years. A "morphing" technique has been used to transform historical time series data based on projected changes in the monthly averages of several climatic variables. The most recently updated TMYx 2004-2018 files [18] were used as the "current" state weather inputs for the morphing process. This process offsets historic weather data based on different future emission scenarios [11].

For a given emissions scenario, there is still uncertainty in how the future climate will evolve due to model limitations and the complex nature of the climate system. For this reason, it is necessary to look at an ensemble of climate projections using a percentile distribution, rather than a single projection [11].

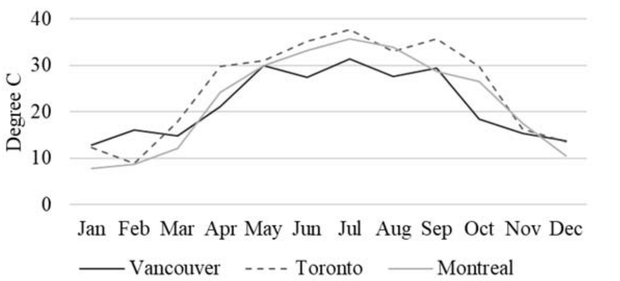

Fig. 4 Monthly maximum dry bulb temperatures by 2050 (RCP 8.5)

This study uses future weather files with a 50th percentile mean temperature increase based on the internationally recognized "business as usual" GHG emissions scenario, known as Representative Concentration Pathway 8.5 (RCP8.5). It is prudent to plan for an RCP8.5 future until global mitigation actions begin to catch up with commitments [10].

The future weather files have been modified based on projections till 2050. Fig. 4 shows that both Montreal and Toronto could experience summertime peak temperatures in excess of 35 °C, while Vancouver is expected to have a relatively milder summer peak right around 31 °C.

IV. Results and Discussion

A. Operable Window Usage

The % hours of operable window use by season (Fig. 5) is directly correlated to the seasonal trends (Fig. 6) in OAT for each city. Since the zone heating setpoint is 22 °C, it is expected that as OAT drops below 20 °C there will be limited opportunity for natural ventilation without causing cold discomfort or activating the heating system. This is particularly true in winter when the OAT is mostly below 10 °C in all three cities, keeping windows closed throughout. Opportunities for window operation in fall and spring are also relatively less due to OAT being mostly < 20 °C, especially in Vancouver. As expected, the highest use of operable windows is observed in summer across all three cities, due to the OAT being > 20 °C for a majority of hours.

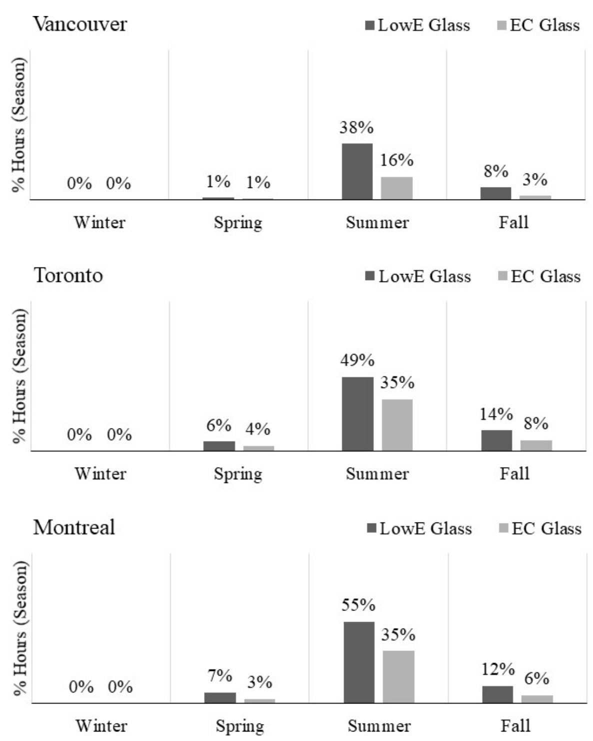

Fig. 5 Hours windows opened (by season and glazing type)

On an annual basis Vancouver has the least hours of OAT > 20 °C (Fig. 6) compared to Montreal or Toronto and thus the simulation reported the least hours of window driven natural ventilation in Vancouver (Fig. 5). This comparatively cold OAT during spring/summer/fall, however, does allow for greater conduction heat loss to take place across the glazing when the windows are closed. In particular, the EC glazing in Vancouver is able to maintain indoor comfort simply by managing the solar heat gain into the unit with greatly reduced need for natural ventilation through open windows. However, in Toronto and Montreal, the relatively higher average OAT necessitates more window operation because any glazing transmitted heat buildup in the space does not dissipate through conduction alone and requires direct ventilation to cool down interior surfaces and reduce the indoor air temperature. While this phenomenon does apply to both glazing scenarios, EC requires far less natural ventilation due to greatly reduced solar gains, with the SHGC in the fully tinted state going down to as low as 0.08.

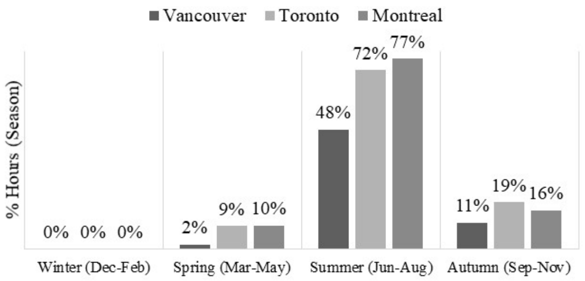

Fig. 6 Hours when OAT > 20 °C

As a result, the scenario with EC glass was found to require between 34-59% fewer annual hours of operable window usage (Fig. 7) to maintain thermal comfort. Maintaining comfort with windows closed is a relevant finding in favor of EC glass, since occupants may not always want to open windows due to concerns with noise, dust, allergens, insects, security etc.

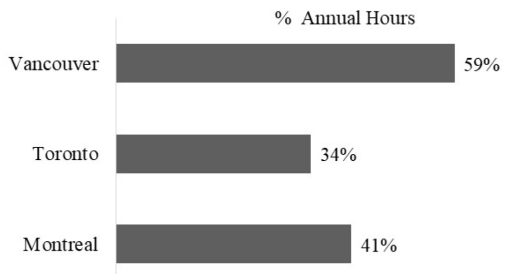

Fig. 7 Reduction in annual hours of window operation with EC

B. Ceiling Fan Usage

Fig. 8 confirms that excluding winter the ceiling fans are running for more than 50% of the time in the Low-E glass window scenario. This is due to the fact that on sunny fall and spring days when the OAT is still too cold to open windows the heat transmitted through the low-E glass builds up in the space but cannot be exhausted quickly enough to the outside through glass conduction alone without added natural ventilation. At that time, the ceiling fan is the only device to mitigate thermal discomfort by increasing zone air speed. In summer, a combination of longer sunny days and hotter diurnal temperatures drive the highest seasonal fan usage.

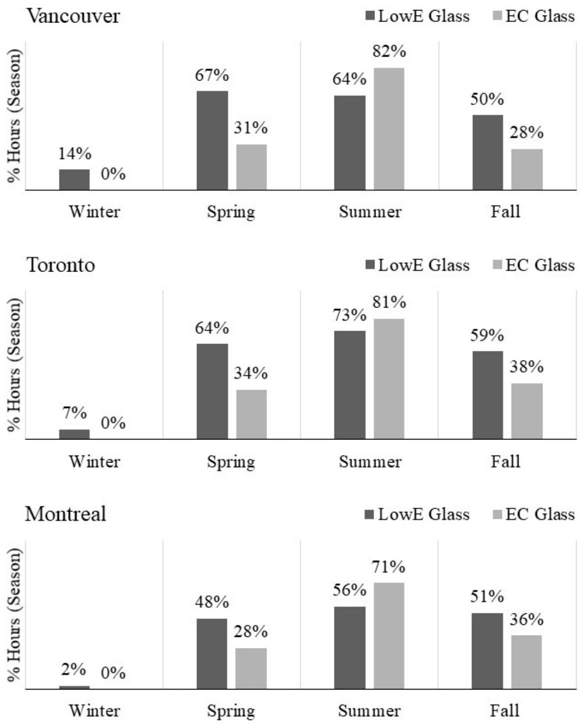

Fig. 8 Hours ceiling fan running (by season and glazing type)

Another reason why the fans are typically working for much more hours relative to the operable windows is because the simulation is set up to use fans first to achieve comfort. In fact, this is why the summer season fan usage is higher for the EC glass scenario in all three cities. In summer, the EC glass is able to maintain more hours of comfort from lower radiant temperatures and use of ceiling fan alone, before the windows need to be opened. This is intentionally setup to reduce reliance on window operation. If the simulation allowed windows to be opened first, then the summer fan usage in the EC scenario would drop below that of the low-E scenario. Even under this constraint the annual ceiling fan usage is still 14-27% less with EC windows (Fig. 9) over low-E.

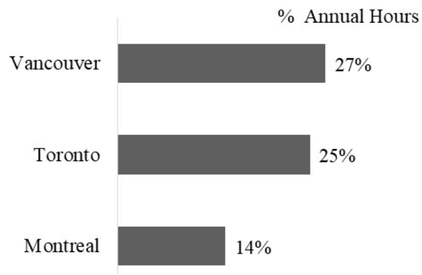

Fig. 9 Reduction in annual hours of ceiling fan operation with EC

C. Effect of EC Glass on Mean Radiant Temperature

Mean Radiant Temperature (MRT) experienced by an occupant at a point in space is influenced by the temperature of surrounding surfaces like floors, walls and windows which release long wave radiation after absorbing shortwave solar radiation. MRT experienced by a person is also affected by shortwave radiation transmitted through the glazing, directly hitting the body. The opening of windows to bring in cooler outdoor air reduces surface temperatures and MRT. In this study a zone average MRT has been simulated assuming an occupant at the center of the thermal zone

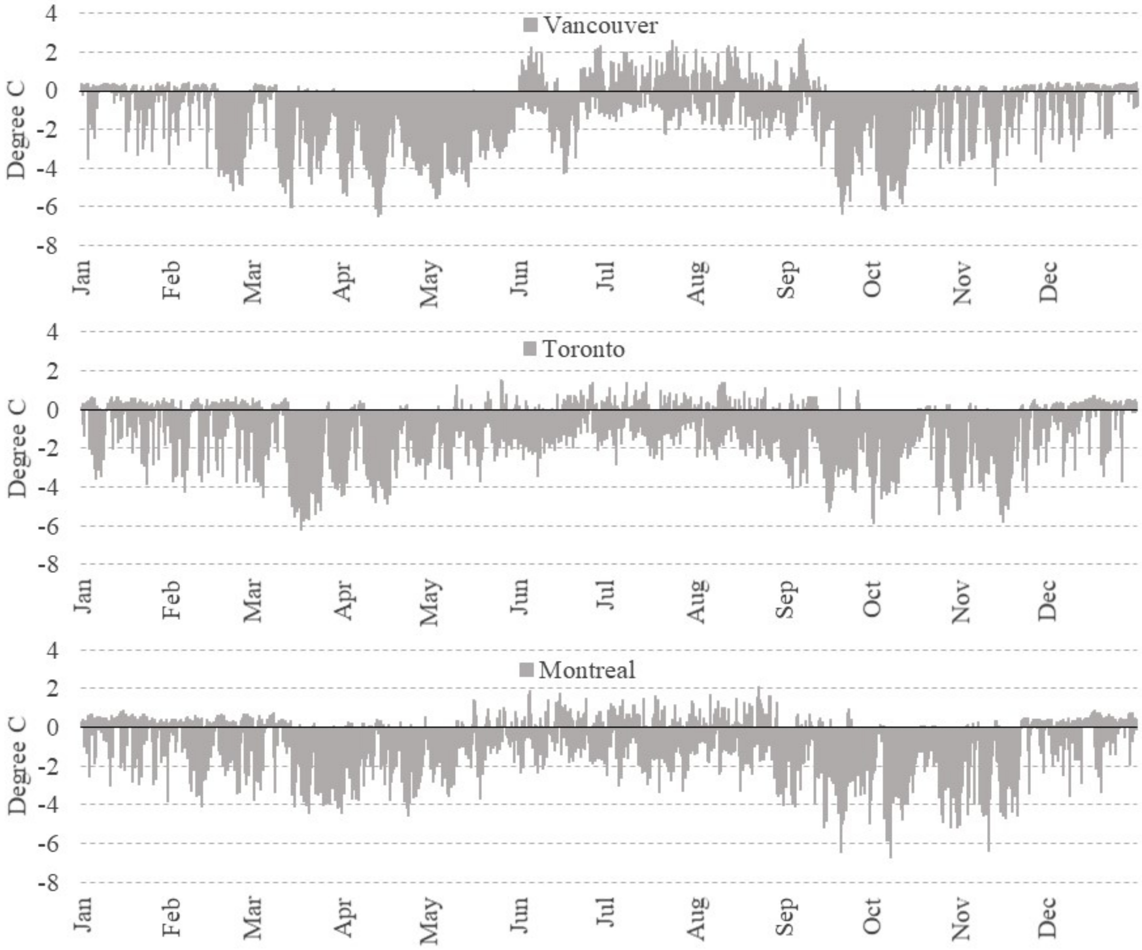

Fig. 10 MRT delta between EC glass and low-E glass with shades

The primary mechanism through which EC windows provide better thermal comfort over a traditional Low-E glass window is the dynamic modulation of solar transmission and a subsequent reduction in the indoor MRT. Fig. 10 shows that over the course of the year and across the three cities, the indoor MRT in the EC glass scenario is up to 6 ℃ lower than the low-E and shades scenario.

The MRT delta between the two glazing scenarios is highest in the fall and spring seasons because during these months there are still several hours of solar radiation through the course of the day, but the windows cannot be always opened due to the relatively low OAT. In the case of low-E windows (even with shades) the solar heat transmitted is much higher than EC windows and without any outside ventilation the inside surface temperatures increase over time, leading to a higher MRT.

The MRT delta is also observed in winter but to a lesser extent because of reduced hours of solar radiation and the significantly colder OAT that helps with conductive heat loss across the glazing area as the indoor space heats up.

The MRT delta between the two glazing options is relatively less in summer because warmer OAT (between 20-30 ℃) provides greater opportunity for natural ventilation through operable windows. This helps to cool down indoor surface temperatures, reducing the MRT delta between the two glazing scenarios. It can also be observed that there are instances in summer when the MRT in the EC glass scenario is higher by 0.5-2℃. This is primarily because compared to low-E the windows with EC glass need to be opened much less to maintain indoor comfort. Thus, in those summer hours when the windows are closed in the EC scenario but kept open in the low-E scenario, the outdoor air flow is helping to reduce the indoor surface temperatures and MRT in the latter.

It should be noted that a higher MRT does not imply discomfort as long as the zone operative temperature (average of MRT and air temperature) is within the ACM limit. The following sections confirm that on an annual basis EC glass is indeed better at maintaining thermal comfort.

D.Annual Thermal Discomfort Analysis

Fig. 11 presents the annual hours of thermal discomfort, sorted into OAT bins. Since the zone heating setpoint is 22 ℃

it is assumed that as OAT goes below 20 ℃ the occupants will typically consider it to be too cold to open windows, especially at OAT less than 15 ℃. Simulations confirmed that due to the high air change rates from open windows, outdoor air at these temperatures can quickly make the zone air too cold and activate the heating system.

The EC glass scenario shows very little discomfort during these hours but in contrast the low-E glass scenario reports much higher hours of discomfort due to indoor heat buildup on cold but clear sunny days. This is particularly acute for Vancouver (Fig. 11 (a)) because compared to the other two cities there are many more hours between May to Sept when the windows cannot be freely opened due to the cold OAT, yet high solar transmission through the low-E glass (with shades) causes the indoor operative temperature to rise beyond the adaptive comfort limit.

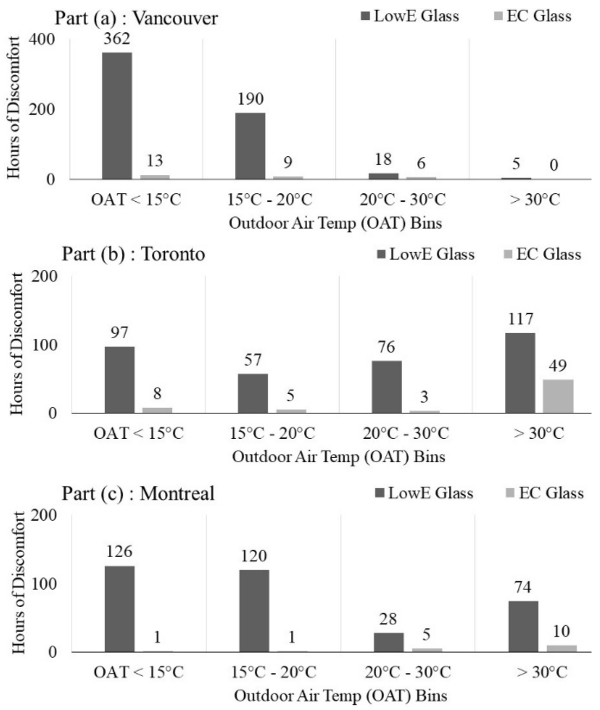

Fig. 11 Annual thermal discomfort hours sorted by OAT bins

One point to consider is that with the windows are closed, the better comfort in the EC glass scenario can be solely attributed to superior solar control with EC, since the U-value of the two glazing options are very similar.

Between 20 and 30 ℃ OAT the windows can be opened as needed for ventilation. As a result, relatively fewer hours of discomfort are reported in this OAT bin for either glazing option. Within this range some discomfort was found to occur in the low-E scenario when the OAT exceeded ~ 27 ℃ on clear sunny days. Since the EC glass can control solar gain more effectively and relies much less on natural ventilation, there is little to no discomfort within this range of OAT.

When OAT is higher than 30 ℃, natural ventilation from windows was found to be have limited to no cooling effect on the zone air. Compared to Vancouver, both Montreal and Toronto have higher projected summer temperatures, as evident from the greater discomfort hours in those two locations for OAT > 30 ℃. In fact, Toronto is expected to have many summer hours with OAT > 35 ℃, at which point the air temperature itself will cause discomfort, with or without solar gain through windows. Even the EC glass could not fully mitigate thermal discomfort at such high OATs through solar control alone and this is the only time during which there are close to 50 hours of discomfort in the EC glass scenario (Fig. 11 (b)).

E. *Compliance with ASHRAE 55*

ASHRAE 55 does not provide an annual threshold for hours of thermal discomfort in naturally ventilated spaces. However, the City of Vancouver Energy Modelling Guidelines state that for buildings with only natural ventilation and no mechanical cooling, it must be demonstrated that interior temperatures do not exceed the 80% acceptability limits as outlined in ASHRAE 55-2010, for more than 200 hours per year for any zone [19]. These guidelines are also referenced in the BC Energy Step Code. This upper threshold of 200 annual hours of thermal discomfort has been adopted for evaluating the relative performance of the two glazing options across the three cities.

Simulation results confirmed that EC glass allows the prototype condo unit to meet this threshold by a significant margin (only 0.2 - 0.7% of annual discomfort hours), across all three cities (Fig. 12). However, with low-E glass it is not possible to meet this comfort threshold despite the much higher hours of operable window and ceiling fan usage. The discomfort hours observed in the low-E glass scenario are between 2 to 3 times more than the upper limit of 200 annual hours.

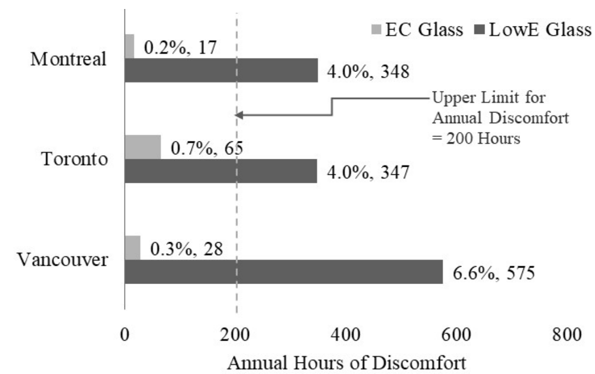

Fig. 12 Annual hours of discomfort (ASHRAE 55 Adaptive Model)

V. Conclusion

Using a typical apartment model and future weather data for three major Canadian cities, this study provides quantitative evidence that EC glazing along with operable windows and ceiling fans has the potential to maintain indoor comfort without mechanical cooling for a majority of the year. The alternative scenario with low-E glass and fabric shades reported much greater annual hours of thermal discomfort, clearly suggesting the need for mechanical cooling to maintain comfort. It is expected that these findings may be applicable for other cities that fall within the same climate zones.

While the apartment model with low-E reported the highest annual hours of thermal discomfort in Vancouver, a vast majority of those hours were found to occur when the outdoor air is presumed to be too cold for windows to be opened. This was an assumption adopted in the study to ensure that the heating system was not activated by cold outdoor air, but it may be argued that occupants can still open windows in such scenarios and this does not constitute a situation which can lead to heat stress. However, if the ambient air itself is very hot then even open windows will provide no relief and prolonged exposure to high air temperatures will likely cause significant thermal discomfort and potentially even heat stress. So, from an overheating point of view, the hours of discomfort reported during high air temperatures in Toronto and Montreal should be of a greater concern.

The thermal model in this study assumes a single well-mixed air volume for each apartment unit, which is typical of energy models that do not use computational fluid dynamics (CFD) for annual simulations. It would be of interest to extend this study to include CFD based analysis to further verify cross ventilation patterns, since the effectiveness of natural ventilation driven airflows is highly dependent on the size and position of the openings in the building. In general, both distribution and velocity of the indoor airflow are strongly influenced by the orientation of building openings with respect to the dominant wind patterns. Once the incidence angles of the wind on the building changes, the pressure fields in the surroundings and around the windows affect the way the indoor air flows through a space [20].

For a naturally ventilated apartment it is also recommended that a ceiling or floor fan is added to each functional area such as living, dining, bedrooms etc. for personal control of air speed when windows cannot be opened, or when the prevailing outdoor wind speed is low.

The primary mechanism through which EC windows provide better thermal comfort over a traditional Low-E glass window is the dynamic modulation of solar transmission and a reduction in the indoor MRT and air temperature. EC windows are very effective in controlling MRT near the facade when tinted, as the incident solar heat is blocked from entering the zone, allowing for space utilization right up to the façade. In the case of typical Low-E glass windows, even with shades down the indoor MRT can continue to be high because shade fabrics absorb the window transmitted solar heat, increasing in surface temperature and acting as a radiator.

An extension of this study would be to replicate this analysis for multi-family buildings in other cities with higher summer temperatures and assess the suitability of using evaporative cooling instead of refrigerant based cooling. As temperatures increase, the relative humidity reduces and evaporative cooling becomes a cost-effective strategy for maintaining comfort. Another interesting topic would be to evaluate the thermal comfort and energy performance of mixed-mode ventilation in conjunction with EC glazing for commercial buildings.

REFERENCES

[1] Brager, G.,& de Dear, R. Climate, Comfort & Natural Ventilation: A new adaptive comfort standard for ASHRAE Standard 55 UC Berkeley: Center for the Built Environment. 2001
[2] Brager, G., Paliaga, G., & de Dear, R. Operable windows, personal control and occupant comfort. UC Berkeley: Center for the Built Environment. 2004
[3] Brager, G.,& de Dear, R. Developing an Adaptive Model of Thermal Comfort ad Preference - Final Report on RP-884. ASHRAE Transactions 104(1) January 1997
[4] Efficiency Canada, 2020. Retrieved from https://www.efficiencycanada.org/what-you-need-to-know-about-the-new-building-codes/
[5] Efficiency Canada, 2020, Retrieved from https://database.efficiencycanada.org/BC/
[6] de Dear, R., V. Foldvary, H. Zhang, E. Arens, M. Luo, T. Parkinson, X. Du, W. Zhang, C. Chun, & S. Liu. Comfort is in the mind of the beholder: A review of progress in adaptive thermal comfort research over the past two decades. The Fifth International Conference on Human-Environment System. Nagoya, Japan. October 29-November 2. 2006
[7] ASHRAE, ASHRAE/ANSI Standard 55-2017 Thermal environmental conditions for human occupancy. American Society of Heating, Refrigerating, and Air-Conditioning Engineers: Atlanta, GA.
[8] Granqvist, C.G., Arvizu, M.A., Bayrak Pehlivan, I., Qu, H.-Y., Wen, R.-T., Niklasson, G.A. Electrochromic materials and, devices for energy efficiency and human comfort in buildings: A critical review, Electrochimica Acta, Volume 259,Pages 1170-1182, 2018
[9] Dutta, R. Modeling an electrochromic window using a multi-criteria control strategy. Building Performance Analysis Conference and Simbuild co-organized by ASHRAE and IBPSA-USA, Chicago, 2018
[10] Climate Projections for Metro Vancouver, Pacific Climate Impacts Consortium, 2016
[11] Dickinson, R., Brannon, B. Generating future weather files for resilience. 36th International Conference on Passive and Low Energy Architecture.
[12] National Energy Code of Canada for Buildings 2017. National Research Council Canada
[13] UIUC, LBNL. 2019. EnergyPlus Application Guide for EMS, U.S. Department of Energy.
[14] Ellis, P. G., Torcellini, P. A., Crawley, D. B. Simulation of energy management systems in EnergyPlus. Building Simulation 2007, Beijing, China.
[15] Lyons, P., Wong, J., Bhandari, M.A. Comparison of Window Modeling Methods in EnergyPlus 4.0, Fourth National Conference of IBPSA 2010, New York
[16] LBNL, 2017. Berkeley Lab Window v7.7.7, Regents of the University of California
[17] Informative Appendix J, ASHRAE/ANSI Standard 55-2017 Thermal environmental conditions for human occupancy. American Society of Heating, Refrigerating, and Air-Conditioning Engineers: Atlanta, GA.
[18] http://climate.onebuilding.org/WMO_Region_4_North_and_Central_America/CAN_Canada/index.html
[19] City of Vancouver Energy Modelling Guidelines v2.0. Amended July 2018
[20] Sacht, Helenice Maria and Marieli Azoia Lukiantchuki. “Windows Size and the Performance of Natural Ventilation.” Procedia Engineering 196 (2017): 972-979.