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PASSIVE STRATEGIES TO IMPROVE MULTI-UNIT RESIDENTIAL BUILDINGS THERMAL COMFORT RESILIENCE IN FUTURE CLIMATE SCENARIOS

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ABSTRACT

In Toronto, many of the thermally massive post-war multi-unit residential buildings (MURBs) do not have central cooling systems to mitigate overheating in summer weather. As the duration and severity of extreme heat events will increase in the future, these building occupants will be vulnerable to greater heat-related morbidity and mortality. Three passive strategies (overhangs, window films and interior roller shades) were simulated in an energy model of a 20-storey post-war MURB and compared against a base case model, to assess their impact on cooling energy consumption under current and future weather conditions. While the interior roller shades were found to be the single most effective measure at reducing cooling energy use, combining all three strategies yielded a 21.3% cooling energy reduction, as well as a 26.7% reduction in unmet cooling hours in the future weather scenario. In order to further reduce unmet cooling hours and address thermal comfort, active cooling systems are required.

INTRODUCTION

Multi-unit residential buildings are a significant source of housing in urban regions, such as Toronto. As of 2016, about 44.3% of the dwellings in the City of Toronto are in apartment buildings with five or more storeys (City of Toronto 2019). However, many of the high-rise apartment buildings were designed with electrical or hydronic baseboard heating systems and are not equipped with central cooling systems. Therefore, the suites can only rely on natural ventilation, fans or packaged terminal air conditioners (PTACs) for cooling (CMHC 2017). As a result of global warming, it is anticipated that the outdoor temperature in Ontario will experience an average annual temperature rise of 2.5°C to 3.7°C by 2050, compared with the baseline average of 1961 to 1990 (MECP 2014). Rinner and Hussain (2011) found that Toronto, the largest urban area in Ontario consisting of dense high-rise buildings, has experienced a 1.6°C to 4°C higher surface air temerpature than the surrounding residential and open areas due to the negative impacts of the urban heat island (UHI) effect. Thus, natural ventilation and air movement driven by fans, which some studies have already shown to be ineffective, will not be an acceptable solution to overheating any more. However, before considering the implementation of active cooling, thermal comfort should first be improved by optimizing the building's passive features in order to minimize energy use. Studies have shown that passive strategies can effectively reduce solar heat gain in high-rise residential buildings. For example, research in Seoul, South Korea shows that the introduction of horizontal overhangs and roller shades results in cooling energy saving potential of 19.7% and 17.7%, respectively (Cho et al. 2014, Oh et al. 2018). Although there has been extensive research of passive strategies under current weather conditions, less is known about how passive strategies can perform under future weather conditions. This study aims to address this gap. This paper examines the effectiveness of passive strategies reducing the cooling load and number of unmet cooling hours in MURBs during summer months, under current and future weather conditions.

METHODOLOGY

An archetypal post-war high-rise MURB was used as the subject of this study. The 20-storey rectangular building is a student family residence at the University of Toronto. It has a floor area of 28,730m^2 and is aligned along the east-west axis. The building has hydronic baseboard heaters and a pressurized corridor ventilation system. There is no central cooling but about one-third of the suites have PTAC units. Suite windows are double glazed with a low emissivity coating and thermally broken aluminium frames, and a window-to-wall area of 27%. Walls are made of concrete block with brick façade and drywall interior without insulation. The calibrated baseline model was generated in eQUEST (version

3.65.7173) by Touchie and Pressnail (2014), then each passive strategy was tested as part of the current study.

Baseline Model

To assess the impact of the passive strategies on cooling energy consumption, PTAC units were added in all suites, and the total cooling capacity of PTACs required to meet the current cooling loads was auto-sized by eQUEST. For all the subsequent models, PTAC capacity was kept the same as in the initial baseline model to assess the number of unmet hours of cooling in each zone.

Each floor of the building was modeled with three zones: a south-facing A/C conditioned suites zone, a north-facing A/C conditioned suites zone, and a non-A/C conditioned corridor zone. Corridors are pressurized with un-conditioned outdoor air supplied by the rooftop air handling unit to meet the minimum ventilation air requirement for suite zones, therefore the corridor zone can be excluded from this study as it does not contribute to the cooling load. The suite cooling setpoint is 26°C, a health-based maximum indoor temperature in apartment buildings during cooling season as specified in Toronto Municipal Code. In order to assess how the building responds to the projected future weather, the energy simulations were run with both current and future weather files, which were historical Canadian Weather Year for Energy Calculation (CWEC) from 1959 to 1989 and future weather generated for the decade of 2040 to 2049 (2040s) by SENES Consultants Limited in 2011. Next, the energy model was run three more times to determine the cooling energy consumption for each passive strategy, and unmet hours in the north and south zones. For each hour that a thermal zone fails to maintain the cooling setpoint, one unmet hour is counted.

Passive Strategies

Three passive strategies were selected for this analysis: overhangs, window films and interior roller shades. The overhang depth was obtained from an online tool developed by Sustainable by Design. Given the inputs of latitude (44°N), south-facing windows and window height of 2.0m (6.6ft), a chart of hourly heat gain from direct sunlight for any day during peak cooling month was generated. Overhangs with a depth of 0.76m (2.5ft) and an equal width to the windows where overhangs were installed right above, result in a minimal heat gain from direct sunlight at solar noon in July for south-facing windows. The adapted size of overhangs was also applied to north-facing windows to compare the change in unmet cooling hours between south- and north-facing zones. According to Ihm et al. (2012), it is beneficial to select glazing unit with low solar heat gain coefficient (SHGC) to reduce cooling energy load in MURB. But after-market window films can be an economical and feasible solution to reducing solar heat gain in a retrofit context. The commercially available interior films selected for this study can be directly applied to the interior side of the window to decrease SHGC from 0.67 to 0.44. Interior translucent roller shades were selected to allow some daylight in but also reduce solar gain. For the purpose of this study, the roller shades were assumed to be closed 100% of the time to maximize solar gain reduction. The input parameters of the selected passive strategies in our study are summarized in Table 1.

Table 1 Input Parameters

PARAMETERS	INPUT VALUE
Overhangs	Depth of 0.76m (2.5ft), full window width, installed right above windows
Window Films	Total Window SHGC: 0.44, VT: 0.38, U: 0.69 Btu/h·ft^2·F
Roller Shades	Interior Translucent Roller Shades Openness: 3%, VT: 0.09

RESULTS AND DISCUSSION

Weather Comparison

Figure 1 compares the average monthly dry bulb temperature and relative humidity between the historical CWEC and 2040s Typical Meteorological Year (TMY) files. Figure 2 shows their corresponding monthly cooling degree days (CDD$_{18}$). As expected, the 2040s TMY features increased average dry bulb temperatures and thus increased cooling degree days.

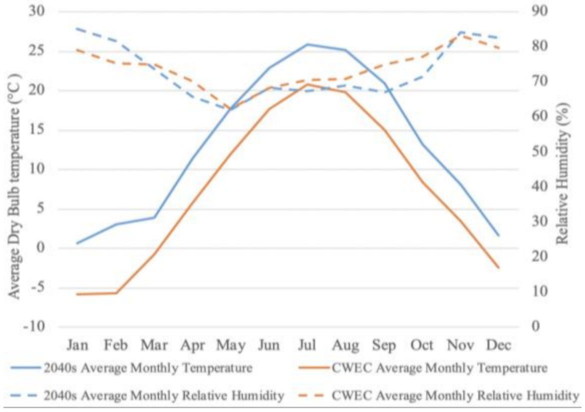


Figure 1 Average Monthly Dry Bulb Temperature and Relative Humidity

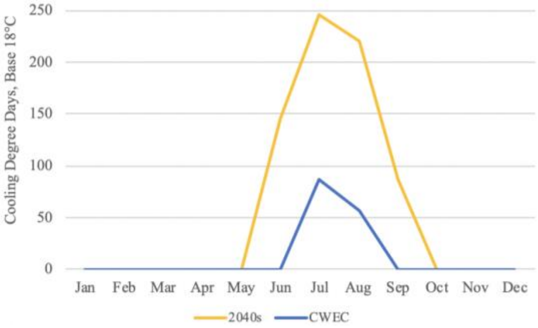


Figure 2 Monthly Cooling Degree Days

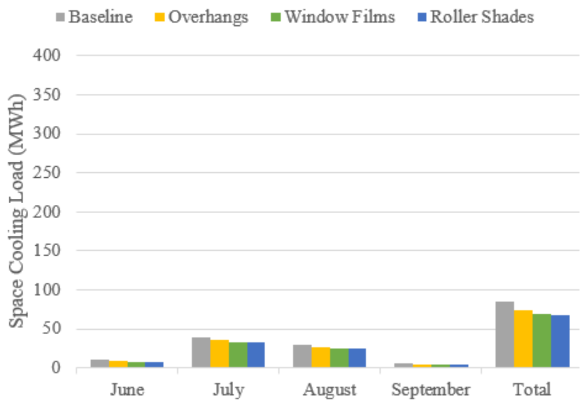
Table 2 compares the results of the base case model with the two different weather files and shows an increase in total cooling energy use intensity (EUI) and unmet cooling hours, as expected.

Table 2 Total Cooling Energy Use

Weather File	Cooling Energy Use Intensity (kWh/m²/yr)	Total Electricity (MWh)	Unmet Cooling Hours
CWEC TMY	3.4	84.6	19
2040s TMY	14.3	355.3	937

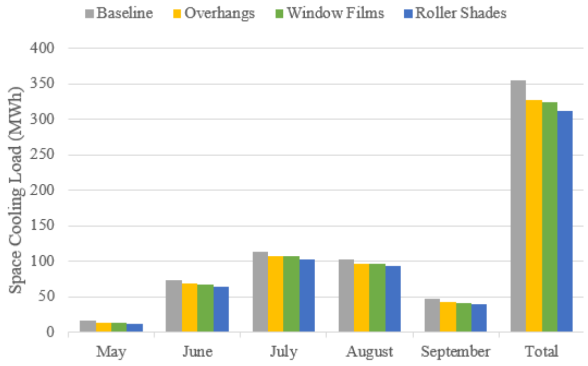
Passive Strategy Comparison

Figures 3 and 4 summarize the monthly space cooling load of the baseline scenario and the passive strategies under current and future weather conditions.



% Decrease from Baseline	June	July	August	September	Total
Overhangs	15.5%	9.0%	13.6%	20.4%	12.2%
Window Films	32.0%	21.2%	26.8%	38.9%	18.1%
Roller Shades	23.3%	14.2%	19.2%	29.6%	20.2%

Figure 3 Monthly Space Cooling Load (CWEC)



% Decrease from Baseline	May	June	July	August	September	Total
Overhangs	20.7%	7.2%	5.6%	6.7%	11.4%	7.9%
Window Films	26.6%	9.5%	6.5%	7.3%	15.0%	8.9%
Roller Shades	24.9%	8.7%	5.9%	6.7%	13.9%	12.1%

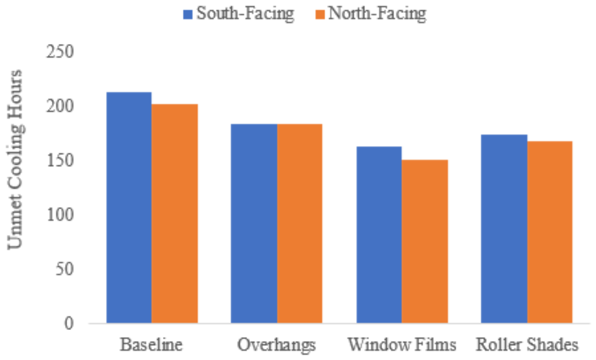
Figure 4 Monthly Space Cooling Load (2040s TMY)

Among the three passive strategies, the roller shades reduce the cooling load most significantly by up to 20.0%, compared with the baseline result under current weather conditions, whereas the overhangs are the least effective strategy. However, roller shades can only reduce the summer cooling by 12.1% under future weather conditions. The change in effectiveness is because the cooling load under future weather file is significantly larger than it is under current weather file.

Unmet Hour Comparison

For the future weather conditions of increased average dry bulb temperature, the auto-sized PTAC's cooling capacity in the current weather baseline model becomes inadequate to meet the cooling setpoint, which consequently, results in longer operation hours without mitigation of the overheating situation.

In the breakdown of the simulation results, the total number of unmet hours for each floor varies. It was found that Floor 19 has the highest number of unmet hours. Therefore, the 19th floor was further analyzed to illustrate the impact of each passive strategy on the total number of unmet cooling hours assuming future weather conditions. As shown in Figure 5, the unmet hours of the south-facing zones are greater than that of the north-facing zones. This is expected, as the south side of the building has a higher solar exposure.



% Decrease from Baseline	Baseline	Overhangs	Window Films	Roller Shades
South-Facing	-	13.6%	23.4%	18.2%
North-Facing	-	8.9%	25.1%	16.7%

Figure 5 Floor 19 Unmet Hours versus Input Parameters under Future Weather Condition

With the introduction of each passive strategy individually, unmet cooling hours for both south- and north-facing zones decrease; however, when comparing unmet hours between south- and north-facing zones, for example, adding overhangs to both zones result in a 13.6% decrease of unmet hours for the south-facing zone and a decrease of 8.9% for north-facing zone. Therefore, implementing passive strategies on the south side of the building is generally more effective to reduce overheating during summer, as expected.

Combination of Multiple Input Parameters

As seen in Figures 3 and 4, implementing a single passive strategy under current weather conditions can ease overheating and reduce the cooling load by 12.2%, 18.1% and 20.2% using overhangs, window films and roller shades, respectively. However, implementing a single passive strategy under future weather conditions is not as effective (a maximum of 12.1% energy saving for roller shades). In order to improve the effectiveness of the selected passive strategies in reducing the cooling energy consumption under future weather conditions, we input all three parameters in one model to simulate a combined scenario. The cooling energy savings for each passive strategy and the combination of all three strategies are summarized in Table 3 as well as their corresponding percentage reduction of unmet hours.

Table 3 Summary of Energy Savings and Unmet Hours Reduction under Future Weather Condition

Input Parameters	**Total Space Cooling [MWh]**	**Unmet Hours**	**% Energy Savings**	**% Unmet Cooling Hours Reduction**
Baseline	355.3	937	-	-
Overhangs	327.1	874	7.9%	6.7%
Window Films	323.6	780	8.9%	16.8%
Roller Shades	312.2	833	12.1%	11.1%
Combine Three Input Parameters	279.5	687	**21.3%**	**26.7%**

As we can see from Table 3, combining all three input parameters results in a 21.3% cooling energy saving and a 26.7% unmet cooling hour reduction under future weather conditions. However, 687 unmet cooling hours indicates an unsatisfactory indoor environment and insufficient cooling capacity, therefore it is necessary to upgrade the existing PTAC system capacity or install other mechanical system such as heat pump to ensure indoor thermal comfort.

CONCLUSION

Passive features of buildings can significantly reduce cooling energy consumption in summer and mitigate overheating. Three strategies, overhangs, window films and interior roller shades, were studied by running energy simulations of a post-war MURB in Toronto. The effectiveness of each strategy is relatively high under current weather conditions but lower under future weather conditions because of the increase in cooling load. Although improving building resilience by implementing multiple passive strategies can reduce cooling energy consumption, active cooling systems are still required to address thermal comfort in these buildings.

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