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LOW-ENERGY ENVELOPE SYSTEMS FOR AN APARTMENT BUILDING IN COLD CLIMATE

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ABSTRACT

The potential to conserve energy in an apartment building in Toronto, Canada through the implementation of an advanced envelope system was explored in this study. This paper illustrates the possibility in reducing a building's energy consumption through an integrated design process (IDP), where research outcomes were incorporated into the architectural design. This study shows that when designing apartment buildings in cold climatic regions, performing energy simulations to identify which measures can be omitted or substituted in the final envelope design can be very valuable for identifying the most effective strategies for improving energy performance.

1.0 INTRODUCTION

Up to the end of year 2006, approximately 1.1 million households, or 6.5% of the total Canadian population were accommodated in apartment buildings (Statistics Canada, 2006). According to the Canada Mortgage and Housing Corporation (2009), the total number of residential household constructions increased 34% from 1998 to 2006, while during the same period apartment constructions increased 64%. Apartment buildings in Canada therefore represent a significant proportion of the national energy consumption and greenhouse gas emission.

Previous studies on low-energy apartment buildings in cold climatic regions have focused on collective benefits of advanced building envelope (Hastings, 2004; Harvey, 2009), but lacked sensitivity analyses in individual envelope characteristics on reducing energy consumptions. The subject of this study is a proposed 12-storey, 163-unit apartment building to be built in downtown Toronto. The designer and developer intended to achieve higher energy efficiency by improving the thermal performances of the envelope system. This study is a vital part of an integrated design process (IDP) aimed to provide simulated data that would influence design decisions at an early stage when it is more likely to have a major impact on the performance of a building (Dell'Isola, 1975; International Energy Agency, 2003). It is the objective of the project team to initiate an ongoing collaborative effort between industry and academia to enhance the performance of not only the subjected building but other related projects. This can deliver improvements in energy-efficiency of a group of buildings resulting in higher quality and asset value, and also providing designers with the knowledge necessary to change their accepted standard practices for apartment building design.

This study examined four low-energy envelope design strategies to reduce space heating and cooling energy consumptions. The strategies involve:

- Insulation level
- Exterior window shading
- Absorptance of external wall
- Window configurations

The first part of the paper will provide an overview of the model used to simulate the building. Results and discussions are then presented, followed by the conclusions of this study and future work.

2.0 BASECASE MODEL

A Basecase model was established with DesignBuilder and EnergyPlus in accordance with the preliminary design drawings provided by the architect. The building (Fig. 1) consists of twelve levels with an amenity penthouse. The total floor area is approximately 12,932 m^2 (139,195 ft^2). DesignBuilder v. 2.0.4 was employed to generate the geometric details of this apartment building (Fig. 1). The DesignBuilder model was then exported to EnergyPlus in specifying operational parameters such as Heating, Ventilating, and Air Conditioning (HVAC) equipments and systems, schedules, sizing, and internal load etc. Simulations were then performed directly from EnergyPlus v.3.1.

2.1. Basecase model parameters

The external wall is composed of precast insulated concrete panel (125mm concrete, 75mm semi-rigid insulation, 105mm concrete) and a layer of gypsum wall board on the interior surface. The internal floor slab is composed of 200mm concrete slab with a layer of gypsum wall board underneath. The flat roof consists of four layers with stone ballast roofing as the outermost layer, followed by 104mm of Expanded Polystyrene (EPS) insulation, 280mm concrete slab, and a layer of gypsum wall board. The thermal resistance values of the envelope components are listed in Table 1. The windows are double glazed units with low-E coating and argon gas-fill. Windows are framed with aluminum. The window-to-wall ratio is 40% as specified by the designer's specifications. Also in accordance to the

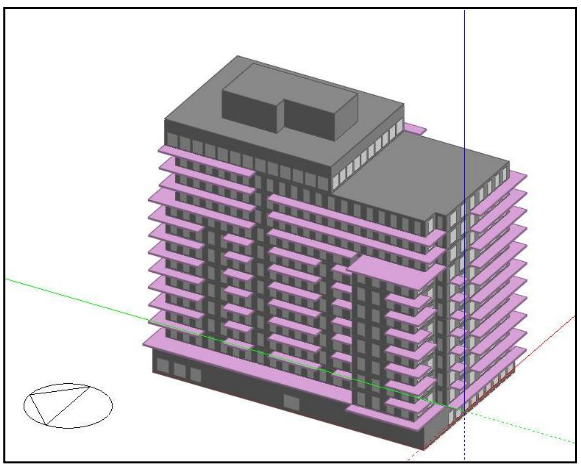

Fig. 1: Geometric representation of the apartment building

designer's specifications, the lighting power density (LPD) is 8 W/m^2 for the corridors, 6.5 W/m^2 for floor 13's amenity space, and 8.6 W/m^2 for ground floor's lobby area; and a LPD of 10 W/m^2 is assumed for apartment units. The apartment units are assumed to have a plug demand of 3 W/m^2 during occupancy, while public spaces have a plug demand of 8 W/m^2. The mean floor areas are 37m^2 for studio units, 59.6 m^2 for one-bedroom units, and 81.4 m^2 for two- bedroom units. An occupancy density of 0.035 people/m^2 is assumed.

The apartments are occupied in accordance with the occupancy schedule as illustrated in Table 2. The infiltration rate is 0.25L/s per m^2 of gross above grade envelope area and minimum fresh air is specified to be 44.5 L/s for one-bedroom and studio apartments and 64.5L/s two-bathroom apartment unit. Both infiltration and outdoor air rates are in accordance with the Procedures for Modeling Buildings to Model National Energy Code for Buildings (MNECB) and Commercial Building Incentive Program (CBIP) (NRCan, 2002). All fresh air is assumed to be delivered by mechanical equipments and that no natural ventilation is available to the unit.

Table 1 – Building envelope thermal resistance

	U (W/m^{2}K)	RSI (m^{2}K/W)
Exterior Wall	0.414	2.42
Slab-On-Grade Floor	2.035	0.49
Interior Floor	2.221	0.45
Flat Roof	0.285	3.51
Windows	2.27	0.44

Table 2 - Occupancy Schedule

	Apartment	Common Area
Monday to Friday	7pm-8am	24 hours
Weekends	9pm-11am	24 hours
Holidays	9pm-11am	24 hours

Two-pipe fan coil units with heat recovery ventilators (HRVs) at 68% effectiveness provide conditioned air to apartment units. The heating set point and setback temperature are set as 22^{o}C and 20^{o}C respectively, Cooling set point and setback temperature are 24^{o}C and 26^{o}C respectively. Large common areas on ground and 13th floor are conditioned with two-pipe air handling units with economizer function for the shoulder seasons. A central modulating boiler with an efficiency of 0.8 and chiller with COP 3.8 provides hot water heating and cold water chilling for the hot and cold water loops, which provides heating and cooling for all the air handling units for the corridors, public spaces, and apartment units.

3.0 RESULTS AND DISCUSSION

On the basis of the building characteristics described above, the heating and cooling energy consumptions were predicted by using EnergyPlus based on the Canadian Weather for Energy Calculations (CWEC) data file from the nearest available weather station (Toronto International Airport). The impact of the four low-energy wall envelope characteristics on heating and cooling energy consumption are investigated and presented in this section.

3.1. Insulation level

The thermal resistance of the external wall was modified by increments of 25mm EPS insulations within the concrete panels. Fig. 2 illustrates the simulation results. As expected, heating consumption decreases as thermal resistance increases. However, increasing the insulation thickness gives diminishing return on the energy saved. This corresponds to studies conducted previously (Yu et al., 2008; Hasan, 1999), for which were taken place in milder or even subtropical climates.

On the other hand, cooling energy consumption remains fairly constant as insulation thickness increases. Monthly simulation results reveal that the building with increased thermal resistance requires space cooling earlier in the year as oppose to Basecase. The heat generated by internal sources and gathered from the sun may not be transmitted to the exterior as readily as Basecase because of the increased thermal resistance. This is in contrary to previous studies conducted in Hong Kong and Changsha, China (Cheung et al., 2005; Yu et al., 2008). However, this finding is aligned to the studies by Masoso & Grobler (2008) and Kim & Moon (2009). Using eQuest, Kim & Moon found that insulation is primarily beneficial for reducing heating energy in winter but has no practical benefit for saving cooling energy consumption in summer. Masoso & Grobler found that cooling load might actually be increased when extra insulation is added on the wall envelope and would depend on the orientation, occupancy patterns, and glazing system etc. of the building. However, it is important to note that natural ventilation was not taken into account in the simulation model.

3.2. Exterior window shades

Previous field studies concerning improving thermal comfort and energy performance with using interior and exterior shades were performed at the twin houses of the Canadian Center for Housing Technology (CCHT) (Laouadi et al., 2008). Results showed an average reduction of 4 ± 2% in heating energy consumption by using external rollshutters versus interior venetian blinds. The external rollshutters used however, were either completely closed or opened throughout the testing period. In this study, Rotatable exterior vertical window shades with high reflectivity slats on both sides were installed on all exterior windows of the building. These shading devices provide shades during overheated periods and allow solar energy to pass through during underheated periods. The shade-to-glass distance was set to 0.015m, the slat width, separation, and thickness were set to be 0.007, 0.019, and 0.001m respectively. Thermal conductivity of the slats was 0.9. Solar transmittance and reflectance were 0 and 0.8 respectively, and emissivity was set to 0.9.

Two control strategies were evaluated. The first strategy is that the operation of the shading system is controlled by a predefined schedule. This is to mimic the case where shades are manually controlled by the occupants in a routine basis. Shades are turned on during summer days and during winter nights. However, relying on the voluntary actions of occupants to use the shading systems in the way they are planned to be used might be problematic (Kuhn et al., 2000; Kim & Park, 2009). Therefore, as an alternative, the second strategy is that shading systems are automatically controlled with motorized shades. With this strategy, shades are turned on during the day when solar radiation incident on the window exceeds 120 W/m^2, at night-time throughout the year, and if there exists a positive zone cooling rate in the zone. For the two control strategies, four slat angles were evaluated, 0^{o}, 30^{o}, 45^{o}, and 60^{o} to the glazing outward normal. With the slat angle set as 0^{o}, the shade is fully extended and the slats are completely closed whenever the shading is on.

As seen in Fig. 3 and 4, the shades are able to reduce the heat loss through windows by an average of 18.9% and 26.2% for the manual and automated control strategy respectively while heat gain through windows is reduced by 4.4% to 8.3% for the manual control strategy and 4.1% to 9.5% for the automated control strategy. Heat loss via long-wave radiation exchange to the exterior is reduced considerably due to the provision of the shades, especially during cold winter nights. The heat flow across the windows was then calculated by subtracting annual window heat loss to annual heat gain and the result is as shown in Fig. 3-4.

As seen, the net heat flow generally increases as slat angle increases. Slats operating with the automated strategy results in a higher net heat flow than the manual control strategy. Both heating and cooling consumptions are reduced by installing window shades in different slat angles (Fig. 5-6), total consumption was reduced by 6.5% to 6.6% for the manual control strategy and 7.9 % to 8.2% for the automated control strategy.

3.3. Absorptance of external walls

Four solar absorptance of the precast wall surface were evaluated, solar absoprtivity at 0.25 (white), 0.45 (light colors), 0.75 (dark colors), and 0.875 (black). The results (Fig.7-8) varied with wall surface color.

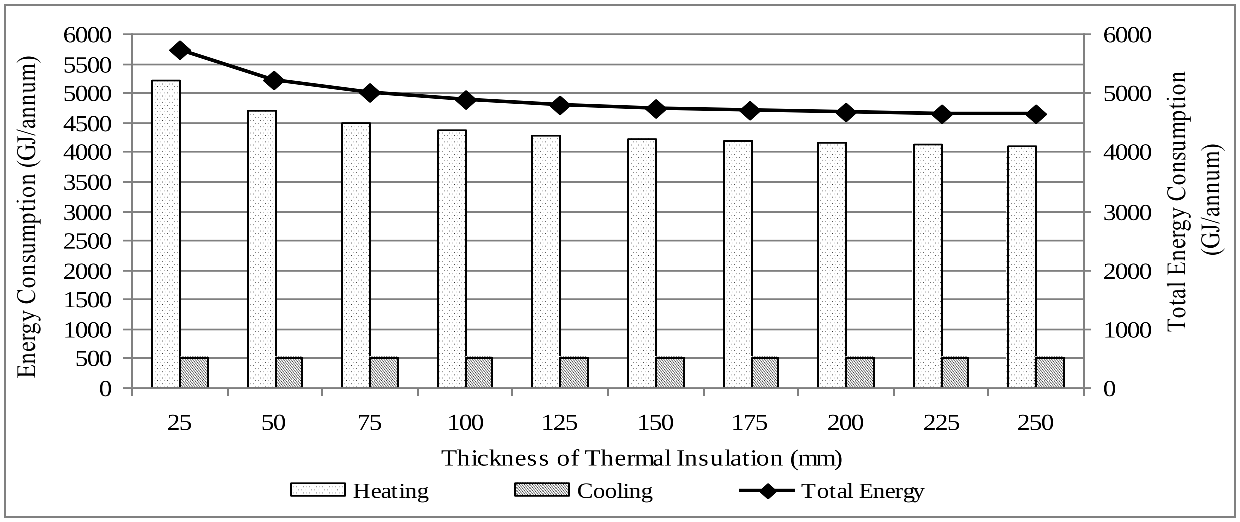

Fig. 2 - Effects of insulation thickness on whole building heating and cooling consumption

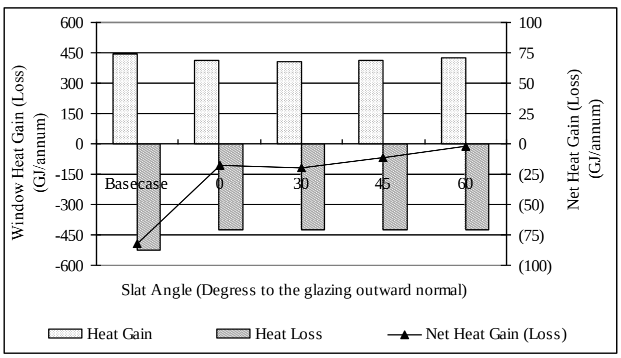

Fig. 3 – Whole building's window heat balance using shades with scheduled control

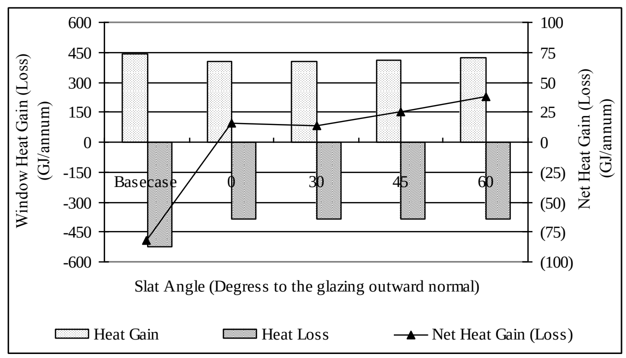

Fig. 4 - Whole building's window heat balance using shades with automatic control

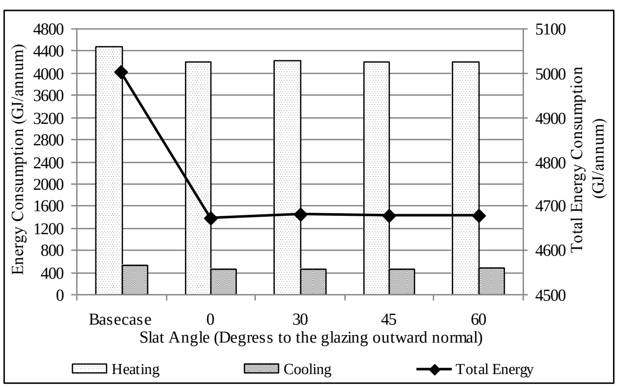

Fig. 5 - The effect of window shades with scheduled control on whole building space conditioning consumption

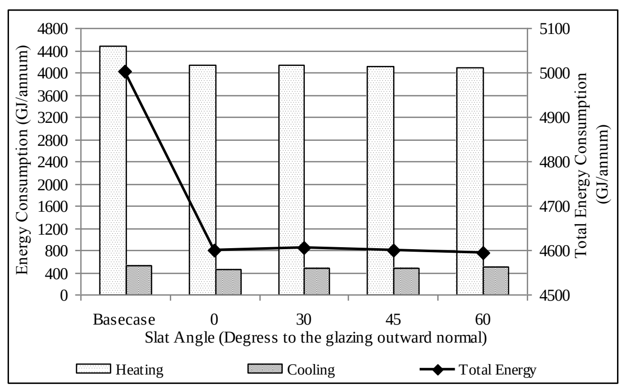

Fig. 6 - The effect of window shades with automatic control on whole building space conditioning consumption

Solar absorptivity and heat loss through external wall display a perfect positive linear relationship. As the absorptance increases (darker surface color), the amount of heat loss through the external wall decreases linearly. Darker surfaces can more readily absorb the solar heat during the day and contribute to the interior heat balance. The reduction in heat loss through exterior wall reduces the heating energy consumption by a mere 1.8%, or 80 GJ/annum when absorptance is increased from 0.25 to 0.875 (Fig. 7); as expected, cooling energy consumption on the other hand is increased by 6.2 %, or 32 GJ/annum (Fig. 8), leading to a decrease of merely 0.9 % for the total consumption. The performance of increasing solar absorptivity on external walls is not as effective as expected and is believed to be due to the climate in Toronto, which is marked by cold winters and relatively warm summers. Simulation results also show that the impact of altering the solar absortpance of the external wall varies with orientation (Fig. 9-10). Heating and cooling load intensity for four apartment units facing different orientations from floor 11 are reported. Heating load intensity decreases in all four orientations as solar absorptivity increases from 0.25 to 0.875. As illustrated in Fig. 9, the south-facing wall displays the steepest negative slope as depicted by the equation of the fitted regression line, followed by north-, west-, and east-facing walls. On the other hand, cooling load intensity in all four orientations increases as solar absorptivity increases (Fig. 10); the south-facing wall displays the steepest negative slope, followed by east-, west-, and north-facing walls.

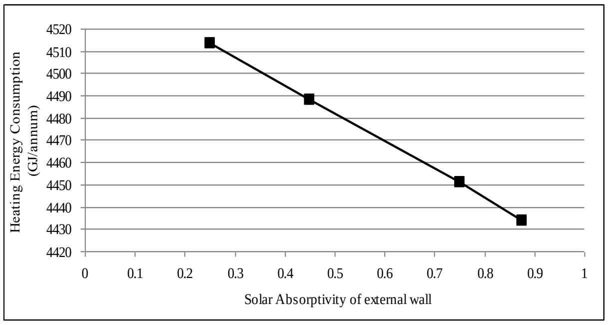

Fig. 7 – Effects of solar absorptivity on whole building’s heating consumption

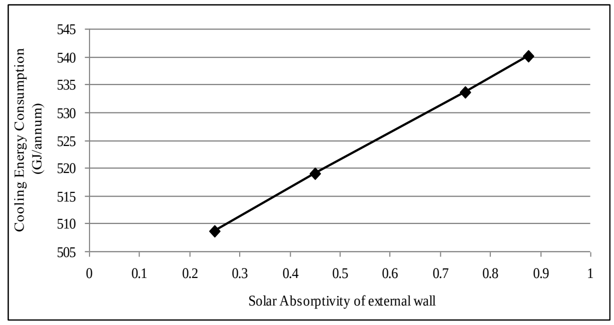

Fig. 8 - Effects of solar absorptivity on whole building’s cooling consumption

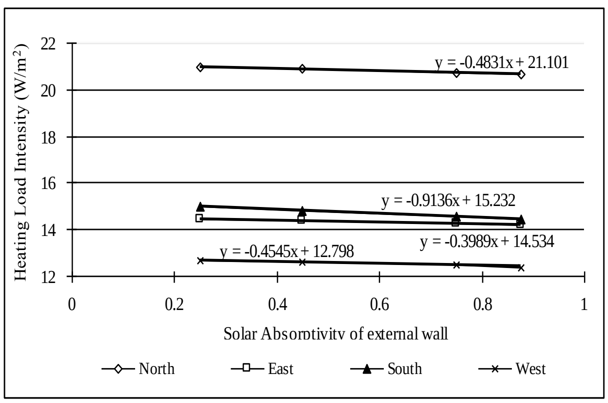

Fig. 9 - Effect of solar absorptivity on heating load intensity with individual units facing different orientations

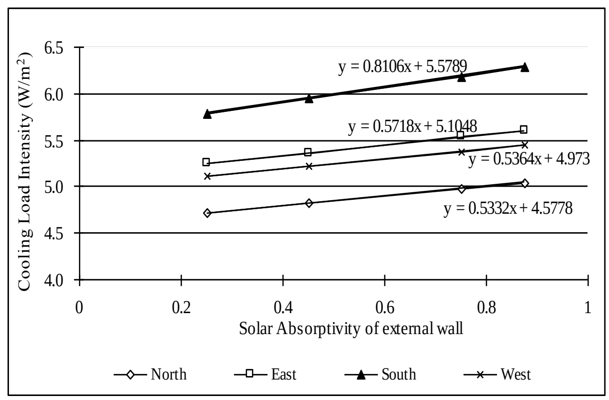

Fig. 10 - Effect of solar absorptivity on cooling load intensity with individual units facing different orientations

3.4. Window configurations

Previous research on low-energy buildings with whole building analysis generally investigated on the performances of installing the same glazing system in all orientations and neglected to study the potential benefits of installing different glazing systems in different orientations. In this study, six window configurations with four types of windows were evaluated. The four types of windows are: Basecase windows (SHGC: 0.44, U-value: 2.27W/m^{2}K) EnergyStar certified windows (SHGC: 0.44, U-value: 1.5W/m^{2}K). EnergyStar certified windows also equipped with high SHGC (SHGC: 0.568, U-value: 1.5W/m^{2}K), and spectrally selective windows (SHGC: 0.274, U-value: 1.34W/m^{2}K). The configurations are as summarized in Table 3.

The effect of replacing the existing window system with the above window configurations was investigated (Fig. 11 & 12). In general, the amount of heat gain increases as the performance of the windows improves from Configuration 1 to 6, except for the case with Configuration 5 to Configuration 6.

As the north-facing windows were replaced with EnergyStar certified windows from Basecase to Configuration 1 (Fig. 11), the heat loss through external glazing is reduced by 6.4% and solar gain through windows is decreased negligibly from Basecase to Configuration 1. This results in a reduction of 2.7% for heating consumption and a 1.1% increase for cooling consumption. As windows from the north, east, and west orientations were replaced with EnergyStar certified windows from Basecase to Configuration 2, the heat loss through external glazing is reduced by 37.2%, which is much more significant than just replacing north-facing windows. Since the building is oriented such that the long sides face east and west, replacing windows on the east and west walls would have a more pronounced impact. As a result, heating and cooling consumption is reduced by 14.8% and 5.3% respectively when compared to Basecase. Configuration 3 is similar to Configuration 2, but with east- and west-facing windows also equipped with high SHGC (0.568). With this configuration, a significant increase of solar gain through the windows is recorded. The amount of solar gain through the windows is increased by approximately 20.4% throughout the year and results in a reduction of 17% in heating consumption compared to Basecase. During the summer, the increased amount of solar gain significantly increases the causes the cooling energy consumption by 12.5%.

The impact of replacing south-facing windows with EnergyStar certified windows from Configuration 3 to 4 is not as significant as all the previous cases. The amount of heating energy consumption is decreased by approximately 3.8% from Configuration 3 with cooling energy consumption remains constant.

Table 3 - Window configurations

Configuration ID	***North-facing*** U-value (W/m^2K)	SHGC	***East-facing*** U-value (W/m^2K)	SHGC	***South-facing*** U-value (W/m^2K)	SHGC	***West-facing*** U-value (W/m^2K)	SHGC
Basecase	2.27	0.44	2.27	0.44	2.27	0.44	2.27	0.44
Configuration -1	1.5	0.44	2.27	0.44	2.27	0.44	2.27	0.44
Configuration -2	1.5	0.44	1.5	0.44	2.27	0.44	1.5	0.44
Configuration -3	1.5	0.44	1.5	0.568	2.27	0.44	1.5	0.568
Configuration -4	1.5	0.44	1.5	0.568	1.5	0.44	1.5	0.568
Configuration -5	1.5	0.44	1.5	0.568	1.5	0.568	1.5	0.568
Configuration -6	1.5	0.44	1.5	0.568	1.5	0.568	1.34	0.274

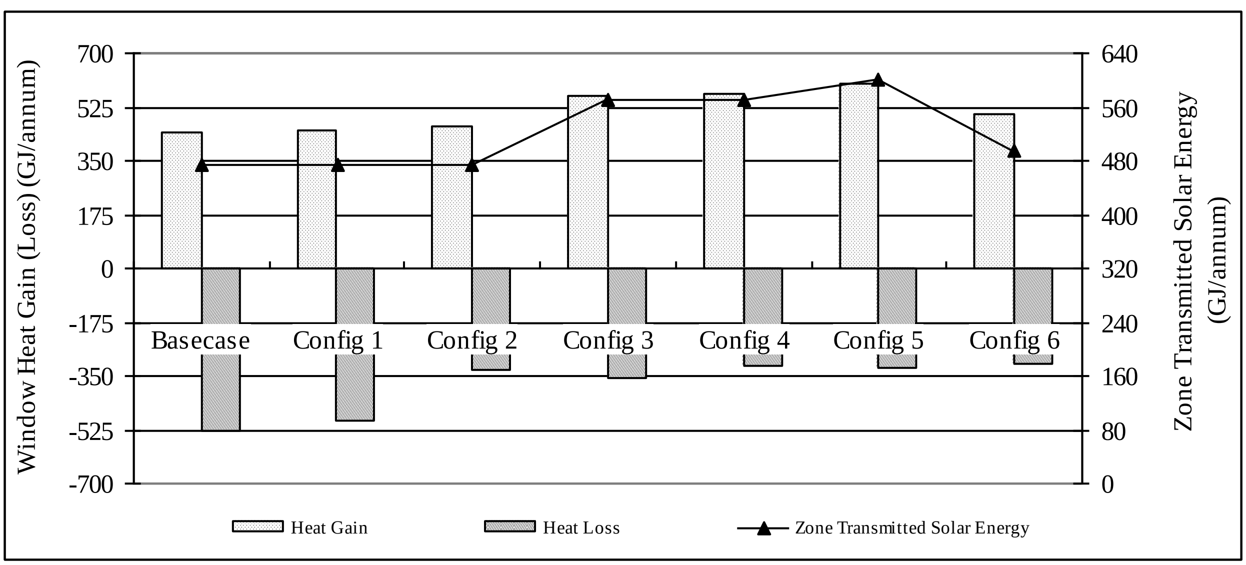

Fig. 11 - Heat gain (loss) and transmitted solar energy with varying window configurations

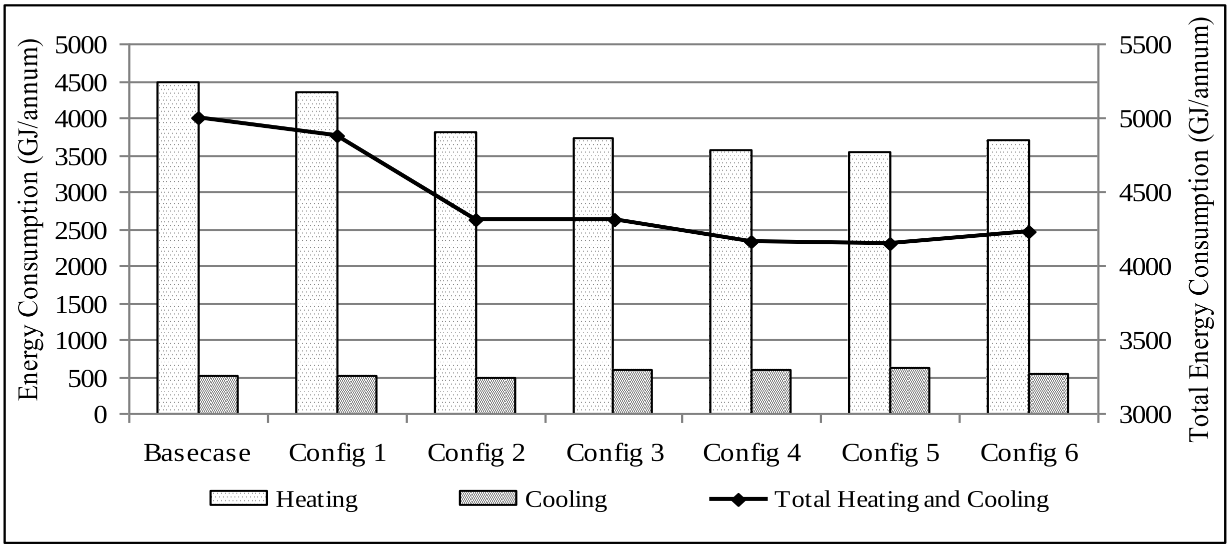

Fig. 12 - Effects of window configurations on heating and cooling consumptions

The south-facing EnergyStar certified windows were equipped with higher SHGC in Configuration 5 to maximize solar heat gain. Solar gain is increased by 5.3% from Configuration 4, which leads to a drop of heating energy consumption of merely 1.2%, but an increase of cooling energy consumption of 4.2%. The combination leads to a net decrease of total energy consumption for heating and cooling of merely 0.4% from Configuration 4. For Configuration 6, spectrally selective windows are used in the west-facing wall to reduce unwanted solar heat gain during the summer. With just replacing the west-facing windows to spectrally selective windows, transmitted solar energy is reduced by 17.6% from Configuration 5. The heating energy consumption is reduced by 17.5% with this configuration and cooling energy consumption is increased by only 1.3% compared to Basecase, a 13.8% drop from Configuration 5.

4.0 CONCLUSIONS

This paper describes the simulation study performed on the building energy performance of a 12-storey apartment building in Toronto with varying building envelope characteristics. Simulation results show that increasing the R-value of the exterior wall gives diminishing returns on the reduction of heating energy consumption. Cooling energy consumption on the other hand remains fairly constant as insulation thickness is increased, which is in contrary to the widely accepted norm that wall insulation helps reduce annual energy consumption for both heating and cooling. The findings on exterior wall R-value signifies that it is important to integrate insulation with other passive strategies such as shading, natural ventilation and glazing design to reduce the cooling energy consumptions. Simply applying rules for energy efficient designs might not be applicable in all circumstances.

The benefits of installing different types of advanced glazing systems on different orientation are made clear. It can be suggested that the energy consumption of this apartment building is more sensitive to window R-values than wall R-values. When R-value of the exterior wall was increased from Basecase at 2.47 m2K/W to 3.92 m2K/W, or 58.7%, heating energy consumption drops 4.5% and cooling energy consumption remains constant. However when the R-value of windows on the east-, west-, and north-facing walls were increased from Basecase at 0.44 m^2K/W to 0.67 m^2K/W, or 51%, heating and cooling energy consumption drops 14.8% and 5.3% respectively. As well, the provisions of exterior windows shades were able to reduce the total heating and cooling energy consumption quite considerably, by up to 8.2%. However, some of the strategies are less effective, namely changing the color of the wall surface.

The simulation results indicate that there is a large potential to decrease the energy consumption in this apartment by employing certain envelope improvements described in this paper. It can be suggested that when designing apartment buildings in Toronto and other locations with cold climates, it is necessary to perform energy simulation to evaluate the energy savings of potential improvements to the envelope system. It is however important to be aware that the simulation results are sensitive to mechanical equipments' specifications. Results might be different by installing a higher efficiency boiler, adjusting the effectiveness of the HRVs for unbalanced flow, etc.

The results of this study should be coupled with an economic analysis that takes into account the investment in the various envelope improvements and the money savings generated by the reduction in cost for heating and cooling and demand charges over the building's lifetime. A life cycle assessment (LCA) should also be undertaken to analyze and access the environmental impacts of the strategies.

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