DESIGN OF A LOW-ENERGY ENVELOPE SYSTEM FOR AN APARTMENT BUILDING THROUGH AN INTEGRATED DESIGN PROCESS: A CASE STUDY

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ABSTRACT

The potential to conserve energy in an apartment building in Toronto, Ontario, Canada through the implementation of an advanced envelope system was explored in this study. This paper illustrates the possibility in reducing energy demand through an integrated design process (IDP), where research outcomes were incorporated into the architectural design. Using the floor plan and schematics provided by the designer, a building energy model was established in an advanced simulation program to evaluate the performances of nine low-energy envelope design strategies in reducing the heating and cooling energy consumption. Through this study, it can be concluded that performing detailed energy simulations early in the design process to identify which low-energy envelope strategies can be omitted or substituted in the final envelope design is crucial in identifying the most effective strategies for improving energy performance. This study also demonstrates the potential of collaboration between academia and industry in generating high performance buildings.

KEYWORDS

low energy envelope system, cold climatic zone, envelope design, thermal mass, wall insulation, energy simulation, apartment building, EnergyPlus

1. INTRODUCTION

The conventional architecture design process is often described as a sequential process, for which the architect proposes a design that determines the general massing scheme, orientation, and building envelope configuration, and the mechanical and electrical engineers will then be asked to suggest appropriate systems for the as-designed building. There is a limited possibility of optimization during the conventional process and opportunities for combined

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benefits are missed, while optimization in the later phases of the process is often costly and impractical due to technical and time constraints.

Integrated Design Process (IDP) has been recently adopted in the North American context and has become established as good practice for high performance building designs (Cascadia Green Building Council, 2010; International Energy Agency ([IEA], 2003). IDP aims to maximize the opportunity for integration and collaboration between building systems early in the design process with major design decisions being made by a broad team of expertise. Professionals with different background share ideas and their expertise at the early phases of the project and therefore IDP often results in an iterative process, where designs for the different building systems progresses in parallel with concepts, ideas, technologies and measures revolving through team members until the building is optimized.

In designing of a high performance building, it is often preferable, if not essential, to optimize passive systems first. Passive systems strategically use the building envelope, building orientation, and geometry to capture and control the various environmental loads such as wind, solar, and rain. In essence, passive systems utilize the resources available on site. On the other hand, active systems import energy from a remote source and rely on systems such as HVAC, plumbing and electrical systems to help meet the heating, cooling, domestic hot water, and lighting loads that passive systems could not otherwise provide. A building that maximizes its passive performance can effectively control the heat flow across the building and results in the building using much less energy from active systems to heat and cool the space (BioRegional, 2009). IDP usually requires additional effort in the pre-design and schematic design phases when compared to conventional design processes. This is so that the architect, engineers, and other members of the team can be involved in suggesting and evaluating strategies with various analyses. Simulating the energy implications of the strategies under consideration provides data that will influence design decisions. Since the degree of the potential impact diminishes rapidly as the project progresses (Lewis, 2004), it is important to carry out simulation analysis at an early phase when it is more likely to have a major impact on the performance of a building.

In 2009, Ryerson University was asked by a local consultant to assess the potential of achieving higher energy efficiency in multi-unit residential buildings by improving the thermal performances through the implementation of an advanced envelope system. The subject of this study is a proposed 12-storey, 163-unit apartment building to be located in the east end of downtown Toronto, Canada. As a vital part of an IDP, this study aimed to provide simulated data that would influence design decisions at an early stage.

The aim was to initiate an ongoing collaborative effort between industry and academia to enhance the performance of not only the subject 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 apartment building is a part of a 15-year community revitalization plan that will eventually consists of apartment buildings and town homes that can accommodate 12,500 people. It is the mandate of the design team to revitalize this neighbourhood as a "green community" with lower CO_2 emissions and energy savings.

Using this apartment building as a case study, this paper aims to illustrate the potentials in improving energy efficiency of new constructions through an IDP. The first part of the paper will provide an overview of the research area on low-energy envelope designs in apartments, followed by a general summary of the demographic and climatic conditions in Toronto, Ontario, Canada. The model used to simulate the building is then described. Results and discussions are then presented, followed by the conclusions of this study and future work.

2. PREVIOUS RESEARCH

At the inception of this project, a combination of theoretical analysis and literature review was undertaken through a series of library research. Case studies concerning developments that were successful under similar site conditions were studied in determining realistic project goals. In addition, new and novel technologies, strategies or materials were researched and evaluated for possible implementation in this project.

In most climatic regions, proper design and combination of insulation and passive components such as direct heat gain from windows, and thermal mass of exterior walls and interior mass etc., can greatly reduce the heating and cooling energy consumption of buildings (Harvey, 2009). Some studies have been done on low-energy apartment building design in cold climates in other parts of the world, predominantly in Europe. Hastings (2004) compared the energy savings for five low-energy apartment buildings in central Europe. Three of the five met the Passivhaus standard (The Passivhaus Institue, 2009) as they attained a space heating demand of less than 15 kWh/m^2/annum (54 MJ/m^2/annum), while the other two were just slightly above the Passivhaus standard. The five apartments are all highly insulated with U-values for the roofs averaging 0.12 W/m^{2}K, walls 0.14 W/m^{2}K, and windows 0.86 W/m^{2}K. Two of them have large window areas (>50%) to capture light and passive solar heat and large balconies to provide seasonal shading. This study also observed that thermal mass in highly insulated and air-tight buildings is useful for providing better summer comfort, as demonstrated in two of the five apartment buildings. However, the apartment buildings studied are only three to four-stories high and therefore findings might not be directly comparable to that of the subjected apartment building, which is considerably bigger in scale. The Canadian Mortgage and Housing Corporation (CMHC) reported a study (CMHC, 2004) in 2004. A 15-storey 112-unit apartment building was subjected to retrofit and the total energy consumption before and after the retrofit were simulated using eQuest (Department of Energy, 2007). The application of Exterior Insulation Finishing System (EIFS) was shown to have decreased gas consumption by 3.2% compared to the basecase. Sealing doors and window perimeters on the other hand, reduced gas consumption by 0.9%. Economic analysis determined that the payback period of cladding upgrade was 147 years, while sealing doors and windows only requires 21.8 years. Unfortunately, the parameters used in the eQuest simulation model, such as occupancy schedule and building envelope configurations were not detailed and therefore the applicability of the results is limited. Smeds & Wall (2007) reported a study, which investigated the key design features of high performance apartments for improving energy efficiency in cold climates. Through simulation with DEROB-LTH, the heating load of a 16-unit apartment building in Sweden built to the target requirement set by IEA Task 28 (IEA, 2005) was approximately 83% less than that of a referenced building built according to the local building code of 2001. Harvey (2009) reviewed literature on low-energy building designs. He summarized the energy savings of two post-retrofitted apartments in Switzerland, and savings up to 88% in heating load were recorded with comprehensive envelope upgrades.

Subsequently, there have been some studies that investigated the effectiveness of individual building envelope characteristics on reducing the heating or cooling energy consumption of buildings. Cheung et al. (2005) conducted a simulation study with TRYSYS on a 42-storey apartment building in Hong Kong and found that up to 29% reduction in cooling energy consumption can be achieved by increasing insulation of the exterior walls. Cheung et al. also reported that the thermal capacitance of the external wall has different effects on the annual required cooling energy and peak cooling load. The reduction of annual required cooling energy was maximized when thermal capacitance was minimized, while reduction of peak cooling load is maximized when thermal capacitance was maximized. It was also reported that up to 12% reduction in annual cooling energy consumption can be achieved by reducing the exterior wall surface solar absorptance by 30% reduction in exterior wall surface solar absorptance. Although this study provided detailed results on the relationship between the cooling energy consumption and the effect of different low-energy envelope design strategies such as insulation, thermal capacitance, color of external wall, glazing system, window area, and shading, the difference in climatic conditions and building design makes the results difficult to be interpreted in the North American context.

Yu et al. (2008) conducted a dynamic simulation with eQuest on a six-storey apartment in Changsha, China and a reduction of 21% and 35% on heating and cooling energy consumption was modelled with combining different low-energy envelope features. Yu et al. considered the implications of where to locate insulation in a precast concrete panel wall system and identified that heating energy consumption is the least with interior insulation, followed by exterior, and middle insulation in precast concrete panels. The study also confirmed that the addition of insulation conforms to the rule of "diminishing return" as the saving for both heating and cooling energy consumption declines for every additional insulation increment. Yu et al.'s study also determined that the differences of solar radiation absorptance with different building exterior surface materials affect the heating and cooling energy consumption quite considerably. Also, the relationship between heating and cooling energy consumption to the window-to-wall ratio follows a strong linear relationship. On the other hand, the effects of varied window-to-wall ratio and presence of shading elements are negligible to the overall heating and cooling energy consumption while different surface absorptance level poses a larger impact on reducing energy consumption. Yu et al. also reported that horizontal shadings of 1.5m overhangs can decrease 4.1% of the cooling energy consumption but increase 1.9% of the heating energy consumption. Vertical shadings with 1.5m fins are similar to that of its horizontal counterpart but it only increases heating consumption by less than 1%. However, there are limitations to this study. Firstly, the study is conducted in a mild climate (HDD 1556) when compared to that in Toronto (HDD 3570). Secondly, the heating and cooling setpoint temperature is 18°C and 26°C, which is not representative with the typical setpoint temperatures in Canada.

In general, the literature review shows that there is a lack of comparative study on the effectiveness of individual building envelope characteristics on reducing the heating or cooling energy consumption of buildings. Nonetheless, the literature provided insights into various low-energy envelope strategies.

Following the literature review, low-energy design strategies applicable to the building of interest were subjected to discussion by the design team members. A total of nine strategies were then shortlisted and subjected to simulation. These strategies include:

- Insulation level
- Thermal mass
- Air-tightness
- Exterior window shading
- Absorptance of external wall
- Thermal break system at balcony connection
- Insulated Concrete Forms
- Exterior overhang
- Different window configurations

3. DEMOGRAPHIC AND CLIMATIC CONDITIONS IN SOUTHERN ONTARIO

The climate in Toronto is marked by cold winters and relatively warm summers. According to the Environment Canada (2008) historical data, the annual average outdoor temperature is 7.5°C and the warmest month is typically July with mean temperature of 20.8°C. The coldest months are January and February, with mean temperatures –6.3°C and –5.4°C respectively. Heating Degree Days (HDD) is approximately 4000. Toronto is located at the south-eastern part of Ontario, for which the province is heating dominated. According to the Natural Resources of Canada (NRCan) (2006), space heating accounts for 55.3% of the total energy requirement in buildings in Ontario, where space cooling merely accounts for 4.4%.

4. THE BASECASE MODEL

A Basecase model was established with DesignBuilder and EnergyPlus simulation tools in accordance with the preliminary design drawings provided by the architects, and mechanical and electrical engineers. The building consists of twelve levels with an amenity penthouse. The total floor area is approximately 12,932 m^2 (139,195 ft^2). DesignBuilder v. 2.0.4.002 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.3.1.0.027.

However, it is important to note that the purpose of simulation is to provide a uniform and consistent mean of comparing the energy performances of different strategies. The actual performance of the building will be dependent on the following, but not limited to: actual weather conditions, quality of installation, proper operation and maintenance of mechanical equipments, and occupant behaviours. For instance, using weather files from different periods, Radhi (2009) reported a difference of up to 14% from simulation results with present and historical weather data. Seligman et al. (1977/78), Filippin et al. (2005), and Bahaj and James (2007) all reported that behavioural aspects, particularly on the control mechanisms such as heating and cooling equipment operations and window openings, play a significant role in energy consumption in residential buildings.

4.1. Basecase model parameters

The external walls are composed of precast insulated concrete panel, which consists of a sandwich of two concrete layers at 125mm and 105mm thick, a layer of 75mm semi-rigid insulation foam in between, and a gypsum plaster layer on the interior surface. The indoor partition walls are each composed of three layers, a sandwich of two gypsum plaster layer with a

FIGURE 1. Geometric representation of the building and simplified floor plan for a typical floor of the apartment.

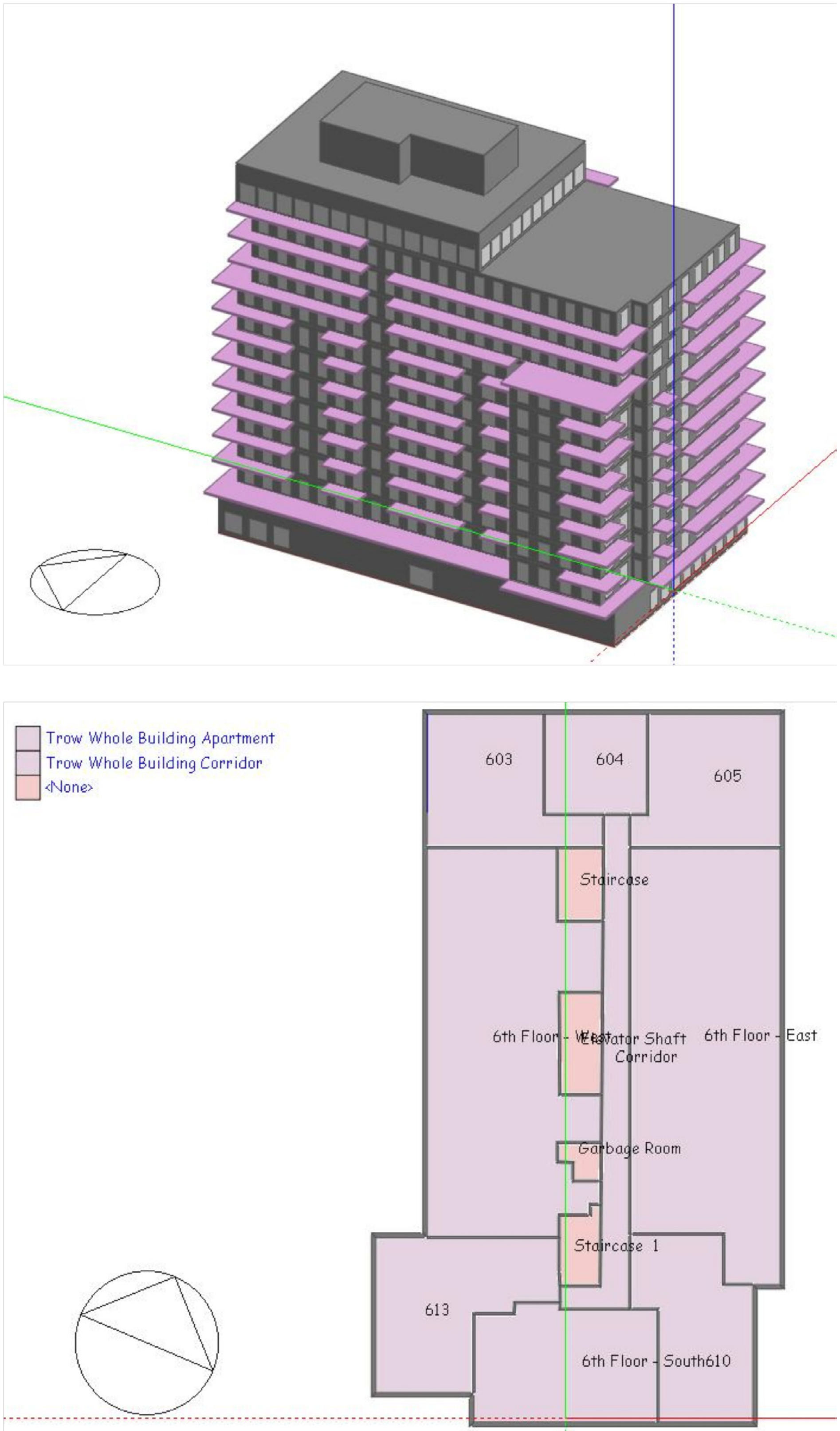


TABLE 1. Thermal properties of materials.

	Density (kg/m^3)	Specific heat (J/kg·K)	Thermal conductivity (W/m·K)
Precast concrete	2400	1000	1.74
Gypsum plaster	1000	1000	0.4
Semi-rigid insulation	20	840	0.036
Expanded Polystrene insulation	25	1400	0.035
Stone Ballast	1840	840	0.36

TABLE 2. Thermal resistance of base case building envelope.

	U (W/m^2K)	Thermal Resistance RSI (m^2K/W)	R (Imperial)
Exterior Wall	0.414	2.42	13.7
Slab-On-Grade Floor	2.035	0.49	2.8
Interior Floor	2.221	0.45	2.6
Flat Roof	0.285	3.51	19.9
Windows (operable and fixed)	2.27	0.44	2.5

100mm concrete layer in between. The floor slab is composed of 200mm concrete slab with a layer of gypsum plaster underneath. The flat roof consists of four layers with stone ballast roofing as the outermost layer, followed by 104mm of Extruded Polystyrene (EPS) insulation, 280mm concrete slab, and a gypsum plaster layer. The properties of the various materials used in the model are summarized in Table 1. The thermal resistance value of the envelope components are as listed in Table 2.

The windows are Argon gas filled, double glazed units, consisting of outer pane of 6 mm thick clear Ti-R glass with low-E coating on the second surface, and inner pane of 4 mm thick glass. Windows are framed with aluminum with thermal break. In accordance to the designer's specifications, all windows have a solar heat gain coefficient of 0.44 and a U-value of 2.27 W/m^2K. Light transmission is set as 0.669 for all fixed and operable windows. Window to wall ratio is assumed to be 42% on the east and west facing façade, and 35% on the north and south facing façade. The total window-to-wall ratio of the building is approximately 40%.

The power intensity of the lighting system is assumed to be 10 W/m^2 for apartment units, 8 W/m^2 for the corridors, 6.5 W/m^2 for floor 13's amenity space, 7 W/m^2 for garbage areas, and 8.6 W/m^2 for ground floor's lobby area. 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. 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 3. The infiltration rate is 0.25L/s per m^2 of gross above grade envelope area, which is in accordance with the Procedures for Modeling Buildings to Model National Energy Code for Buildings (MNECB) and Commercial Building Incentive Program (CBIP) (NRCan, 2002). With the envelope area and volume at 7,124m^2 and 38,800m^3, an air change rate of 0.17 ACH

TABLE 3. Occupancy Schedule.

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

at normal operating condition was employed in the model. This air infiltration rate lies within the range reported in previous studies by different research groups. Feustel & Diamond (1998) from Lawrence Berkeley National Laboratory (LBNL) reported an air infiltration of 0.2 for a 150-unit apartment building in Chelsea, Massachusetts; Emmerich et al. (2005) reported an average of 0.232 for four-storey apartment buildings across the USA. 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 with a kitchen exhaust and a dryer. All fresh air is assumed to be delivered by mechanical equipments and that no natural ventilation is available to the unit.

The HVAC system for the Basecase model is a two-pipe fan coil units with heat recovery ventilators at 68% efficiency in each apartment unit. The heating set point and setback temperature are set as 22°C and 20°C respectively, Cooling set point and setback temperature are set as 24°C and 26°C. Corridors are served by an air handling unit providing ventilation of 0.3L/s·m^2 (0.06 cfm/ft^2). Large common areas on ground and 13th floor are conditioned with two-pipe air handling units with economizer function for the shoulder seasons. Each unit is equipped with a supply fan, a return/exhaust fan, heating and cooling coils, and heat recovery ventilators at 68% efficiency. The actual building is connected to a district energy system, but for the purpose of this study, a central plant is assumed to supply space heating and cooling. A central boiler with COP 0.8 and chillier 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.

5. RESULTS AND DISCUSSION

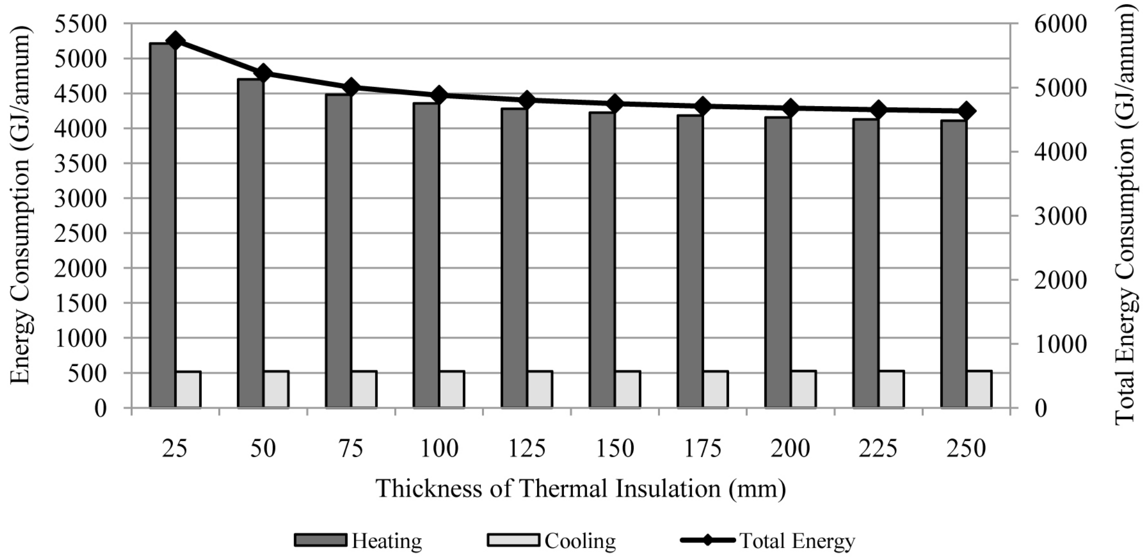
On the basis of the building characteristics described above, the heating and cooling energy consumptions were predicted by using EnergyPlus based on the Canadian Weather for Energy Calculations (CWEC) data file from the nearest available weather station (Toronto International Airport). Various low-energy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

5.1. Insulation level

Different levels of thermal resistance can be achieved by adding EPS thermal insulation to the external walls of the models. 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 energy consumption decreases as thermal resistance increases; insulation reduces the heat transfer rate and thereby reduces the energy requirement for space heating. However, increasing the insulation thickness gives diminishing returns on the energy saved. This corresponds to studies conducted previously (Yu et al., 2008; Hasan, 1999; Dombayci et al., 2006), for which were taken place at 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 insulation requires space cooling earlier in the year as opposed 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 insulation. This is in contrary to previous studies conducted by Cheung et al. (2005) and Yu et al. (2008), where reductions in cooling energy consumption was recorded with incremental increase in insulation thickness in apartments in Hong

FIGURE 2. Effects of insulation thickness on heating and cooling energy consumption.



Kong and Changsha, China. However, this finding is aligned to the studies by Masoso & Grobler (2008) and Kim & Moon (2009). Using eQuest, Kim & Moon (2009) conducted a simulation study on a low-rise residential house in Detroit, Michigan and 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 (2008) 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.

5.2. Thermal Mass

Simulation results also show that changing the thermal mass of the external wall has trivial effects on the heating and cooling energy consumption (Fig. 3-4). The exterior wall configuration was manipulated to investigate on the impact of thermal mass on the space conditioning energy consumption of the building. The EPS insulation layer is moved from the middle of the external wall to the inner and outer surface and the thickness is increased by increments of 50mm. The simulation results do not indicate any significant saving due to thermal mass by manipulating the location of the EPS insulation layer. The heating and cooling energy consumption differences observed by varying the configuration of the external wall are too small to be significant to conclude any potential saving.

5.3. Air-tightness

A literature review was conducted on previous studies on air-tightness in apartment buildings in North America and reveals that while air infiltration represents a major contribution to heating demand (CMHC, 2001), the complexity of the structural, mechanical, and thermal systems of apartment buildings makes it difficult to fully understand and predict the air-tightness levels in this type of building (Persily, 1999; Proskiw and Philips, 2008; Genge, 2009). Current

FIGURE 3. Effects of wall configurations on heating energy consumption.

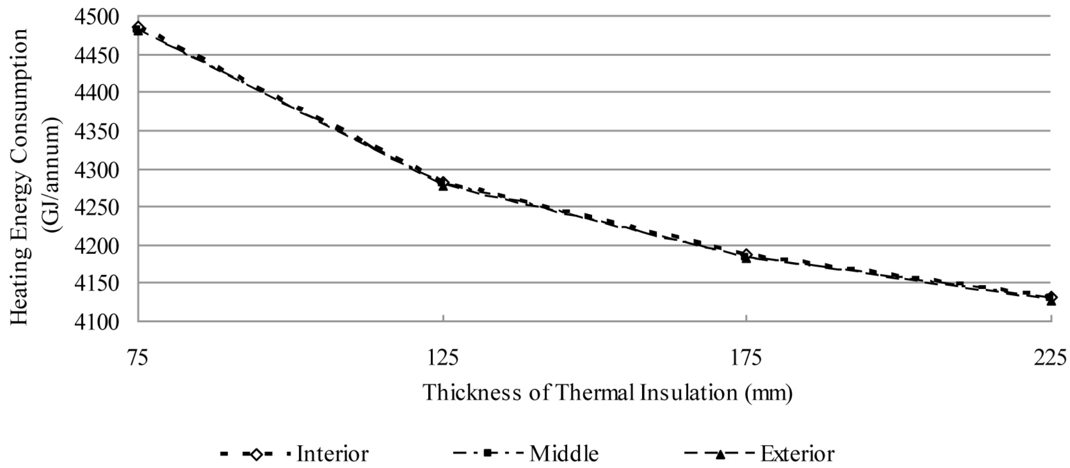
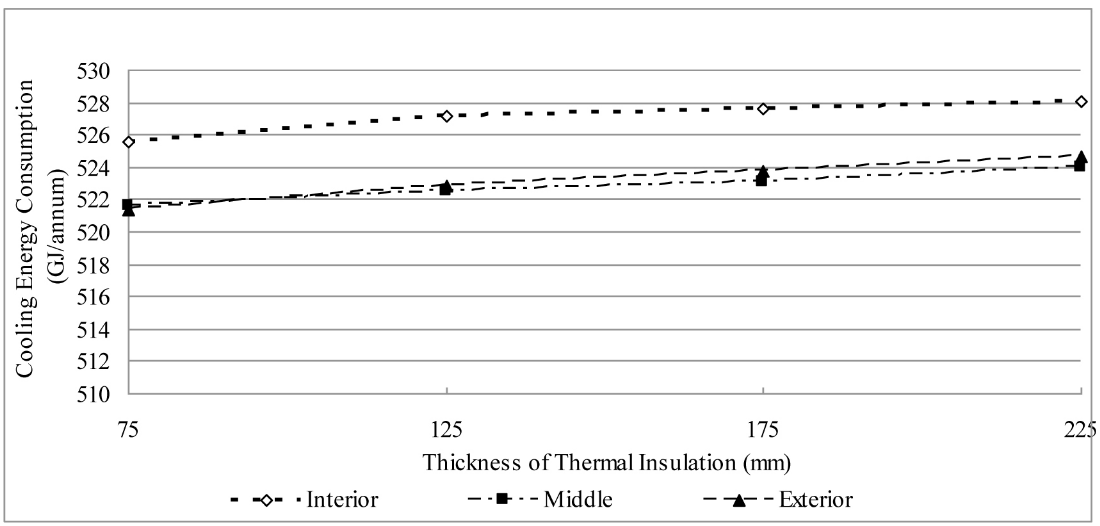


FIGURE 4. Effects of wall configurations on cooling energy consumption.



building certification programs such as LEED also do not recognize the impact of improving air-tightness in reducing the heating and cooling energy consumption of buildings.

Sherman & Chan (2004) reviewed over 100 publications relating to air-tightness around the world and found that while more than 100,000 low-rise residential houses have been tested and documented since blower or fan door testing was introduced in the 1970s, only less than 500 units in apartment buildings have been tested for air-tightness worldwide. The sample set for apartment buildings is practically insignificant in comparison to the vast number of low-rise residential houses tested and documented. The largest database of low-rise residential houses is maintained by the Energy Performance of Buildings Group at Lawrence Berkeley National Laboratory (LBNL) which has over 73,000 testing data from the USA. No such database exists for apartment buildings. Typical values for the different category of air-tightness level in low-rise houses can be found in the ASHRAE Handbook of Fundamentals

TABLE 4. Air-tightness values as per ASHRAE handbooks—fundamental.

	NLR_{75} (cfm/ft$^2_{envelope\ area}$)	NLR_{75} (L/s·m$^2_{envelope\ area}$)
Leaky	0.6	0.026
Average	0.3	0.013
Tight	0.1	0.004

(2005) and is as summarized in Table 4 in normalized leakage rate (NLR) (cfm/ft^2 and L/s·m^2 at 75 Pa). No such baseline values are provided for apartment buildings.

CMHC (1993) evaluated the air leakage rates through the building envelope in ten buildings across Canada. The results indicated the NLR ranges from 2.10 to 3.15 L/s·m^2 at 50 Pa (0.54 – 0.90 cfm/ft^2 at75 Pa) during suite fan depressurization testing. In a more recent Canadian study (Finch, 2007), four buildings in Vancouver, BC were air leakage tested. Two of which are four-storey wood-frame apartments with one of them built in the early 1990's and the other one built in 2002. The other two are six- and 26-storey high concrete framed apartments built in the early 1990's and late 1980's respectively. The investigation showed that the two wood-framed buildings have much higher air leakage rates than the two concrete-framed buildings. The results indicated that NLR were found to be in the range of 0.56 –1.28 L/s·m^2 at 50Pa (0.14–0.33 cfm/ft^2 at 75Pa) for the two concrete frame buildings and 1.74 – 3.59 L/s·m^2 at 50Pa (0.45–0.92 cfm/ft^2 at 75Pa) for the two wood framed apartment buildings.

Table 5 lists the reported air-tightness level of apartment buildings in North America by different research groups. Data has been converted to normalized leakage rate (cfm/ft^2 and L/s·m^2 at 75 Pa) using the conversion formulas from Chapter 27 of the 2005 ASHRAE Handbook – Fundamentals.

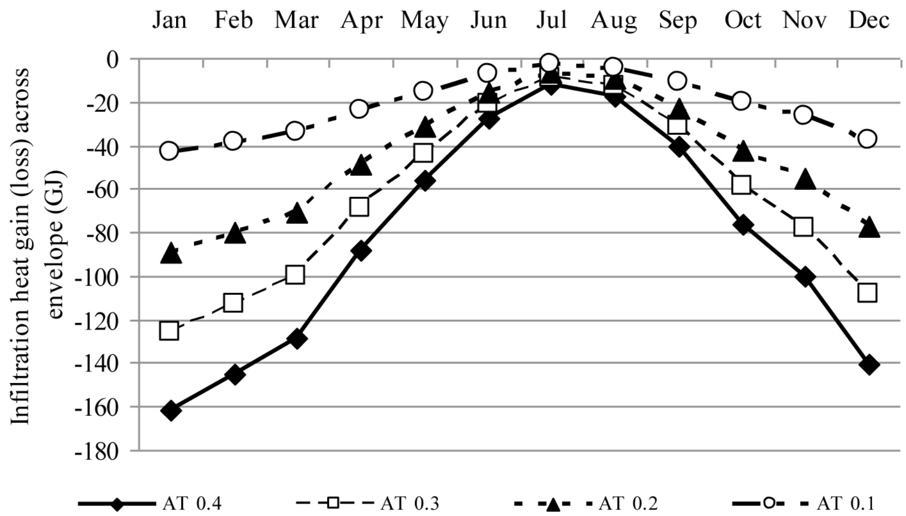
There is little consistency between the tests, and each building will likely be unique depending on workmanship, construction practices, details, and materials used. Nonetheless, these previous tests provide some guidance on the range of air leakage values to be used in simulations. The model was simulated with different air-tightness levels by changing the air change per hour (ACH) value of the envelope system. ACH 0.1 (0.11 cfm/ft^2 or 0.0048 L/s·m^2 at 75Pa) to 0.4 (0.44 cfm/ft^2 or 0.0193 L/s·m^2 at 75Pa) with ACH 0.1 increments.

As illustrated in Fig. 5, infiltration causes heat loss throughout the entire year for all four scenarios. The amount of heat flow differs significantly throughout the year. In January, the difference in amount of heat loss through the envelope is approximately 3.4 times, or 118.78 GJ from ACH 0.4 to ACH 0.1; in July, the difference drops to 3.2 times, or 8.76 GJ. The amount of heat loss via infiltration is comparable to the conductive heat loss via exterior wall. Conduction heat loss through building envelope is recorded to be 104.62 GJ and 44.34 GJ in January and July respectively in Basecase. As seen, infiltration therefore contributes to a major contribution to the heating energy consumption of the building.

TABLE 5. Reported air-tightness levels from previous studies.

	NLR_{75} (cfm/ft$^2_{envelope\ area}$)	NLR_{75} (L/s·m$^2_{envelope\ area}$)
CMHC (1990)	0.23	0.01
Persily (1999)	1.5	0.0658
Sheltair Scientific (1999)	0.49	0.0215

FIGURE 5. Infiltration heat gain (loss) across envelope system with varying air-tightness levels.



Because infiltration plays a much more significant role in winter than in summer, the impact on heating energy consumption is more pronounced than cooling energy consumption with the different ACH levels. As illustrated in Fig. 6, heating energy consumption is reduced significantly from 6074.3 GJ/annum to 3917.5 GJ/annum, or 35.5% as the air-tightness of the building improves from ACH 0.4 to ACH 0.1. In the meantime, by improving the air-tightness of the building, cooling energy consumption decreases marginally from 537.7 GJ/annum to 527.3 GJ/annum, or 1.94%. As shown in Fig. 7, peak cooling demand on the other hand is reduced from 145.1 kW to 130.2 kW, or 10.2%. This illustrates that the peak cooling load can be reduced quite considerably by improving the air-tightness of the building, which could potentially lead to a reduction in sizing of the mechanical equipments.

FIGURE 6. Effects of air-tightness level on heating and cooling energy consumption.

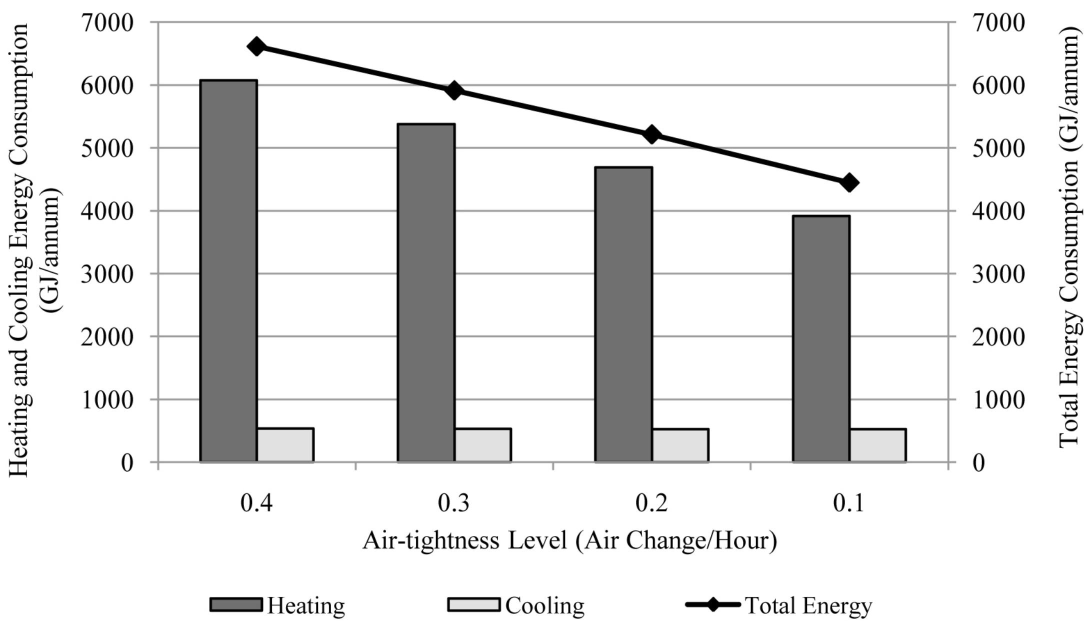
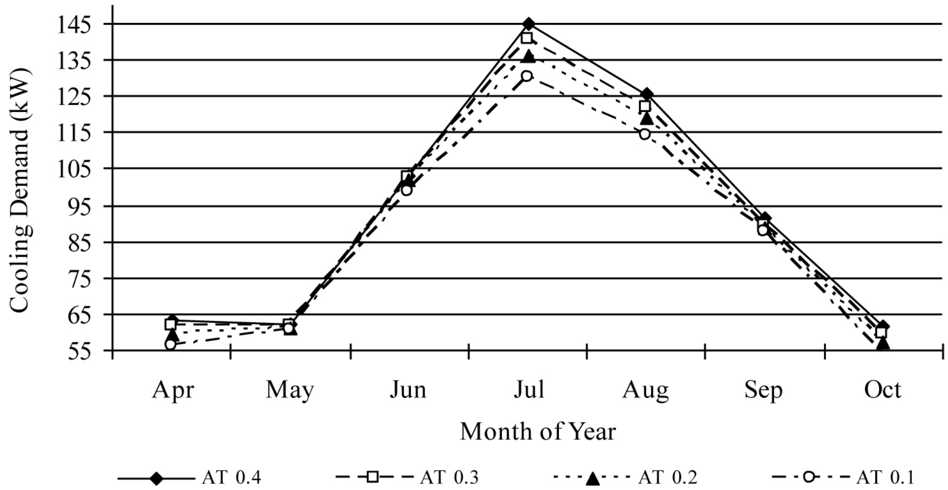


FIGURE 7. Effects of air-tightness level on cooling demand.



5.4. Exterior window shades

The research area on integrating advanced glazing and innovative day-lighting/shading systems in lowering both the lighting and space conditioning load is quite extensive (Kuhn et al., 2000; Tzemoelikos, 2007), but it is not the objective of this study to evaluate the interaction of day-lighting effects with shading system. This part of the study focuses purely on the benefits of installing exterior window shades in reducing heating and cooling energy consumption.

Retractable exterior vertical window shades with high reflectivity slats on both sides were installed on all exterior windows on all four sides of the building. These rotatable and retractable 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 defined 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 to avoid unwanted solar gain and during winter nights to minimize heat loss from the glazing system by means of radiant exchange to the exterior. 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) found that manual control of shading systems at offices might increase the overall energy consumption if the shading systems are not operated properly. Scott et al. (2001) found that the participation rate of adjusting shades during hot summer days to prevent overheating is quite low when compared to other energy conservation actions such as turning off unused lights and adjusting thermostat set-points when house is not occupied. 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. When the shadings are on, they fully cover all of the windows except the frame; when they are off, they are retracted and do not cover the windows. For the two control strategies, four slat angles were evaluated, 0°, 30°, 45°, and 60° to the glazing outward normal. The slats are parallel to the glazing and faces outdoor when the slat angle is set as 0°. With the slat angle set as 0°, the shade is fully extended and the slats are completely closed whenever the shading is on. This slat angle maximizes the overheating protection when it's on, but ignores the need for visual contact to the exterior.

As seen in Fig. 8 and 9, 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

FIGURE 8. Window heat balance using shades with scheduled control.

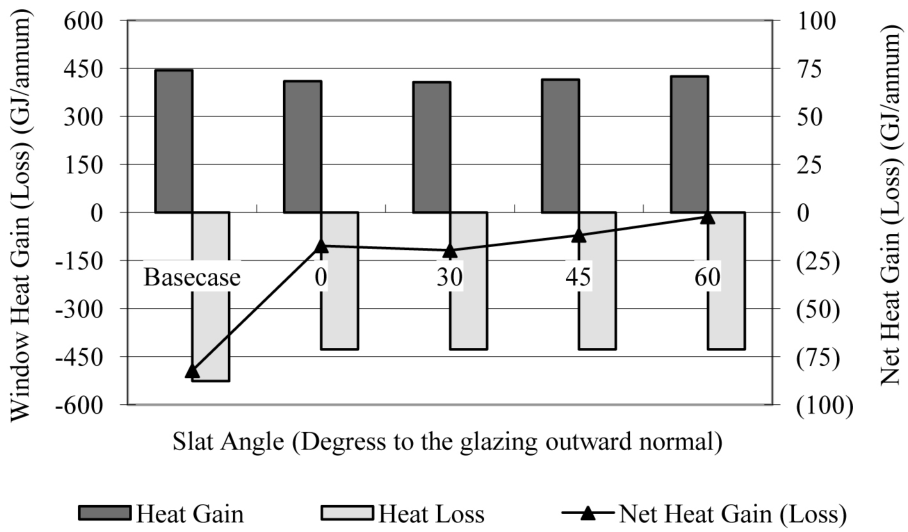
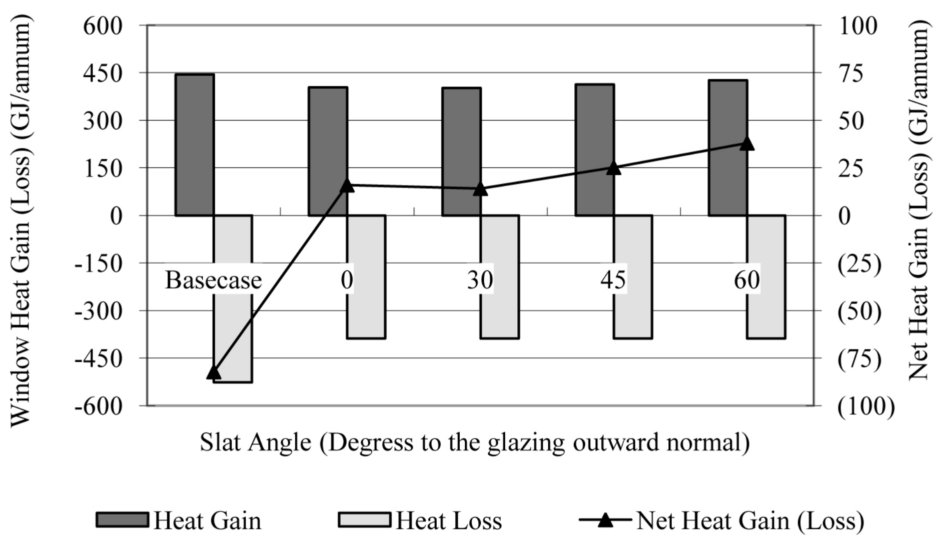


FIGURE 9. Window heat balance using shades with automatic control.



during cold winter nights. The amount of heat gain decreases as slat angle increases from 0° to 30° in both cases. However, as slat angle further increases from 30° to 60°, the amount of heat gain increases (Fig. 8-9) and monthly results reveal that the occurrence of increase in heat gain is during summer cooling months. During winter heating months, systems with lower slat angles allows more solar heat in passing through than systems with higher slat angles. Therefore systems with lower slat angles are more effective in blocking unwanted solar heat gain during the summer and allowing more solar heat into the space during winter. 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. 8-9. As seen, for both control strategies in general, the net heat flow becomes more positive, which results in net heat gain as we increase the slat angle. The automated strategy has a higher amount of net heat flow than the manual control strategy. Net heat losses were recorded for all angles controlled by the manual control strategy, while net heat gains were recorded for the automated control strategy. Both heating and cooling energy consumptions are reduced with installing window shades in different slat angles (Fig. 10-11) which leads to a drop of total energy consumption of 6.5% to 6.6% for the manual control strategy and 7.9 % to 8.2% for the automated control strategy.

5.5. Absorptance of external walls

Solar absorptance of a wall surface depends on its color and surface texture and poses an effect on the surface temperature. Emissivity is a measure of the ability of a material to emit thermal radiation. Four solar absorptance of the precast wall were evaluated, solar absoprtivity at 0.25 (white), 0.45 (light colors), 0.75 (dark colors), and 0.875 (black). The results (Fig.12-13) varied with wall surface color. Solar absorptivity and heat loss through external wall displays a perfect positive linear relationship. As the absorptance increases (darker surface color), the amount of heat loss through the external wall decreases. Darker surfaces can more readily

FIGURE 10. The effect of window shades with scheduled control on space conditioning energy consumption.

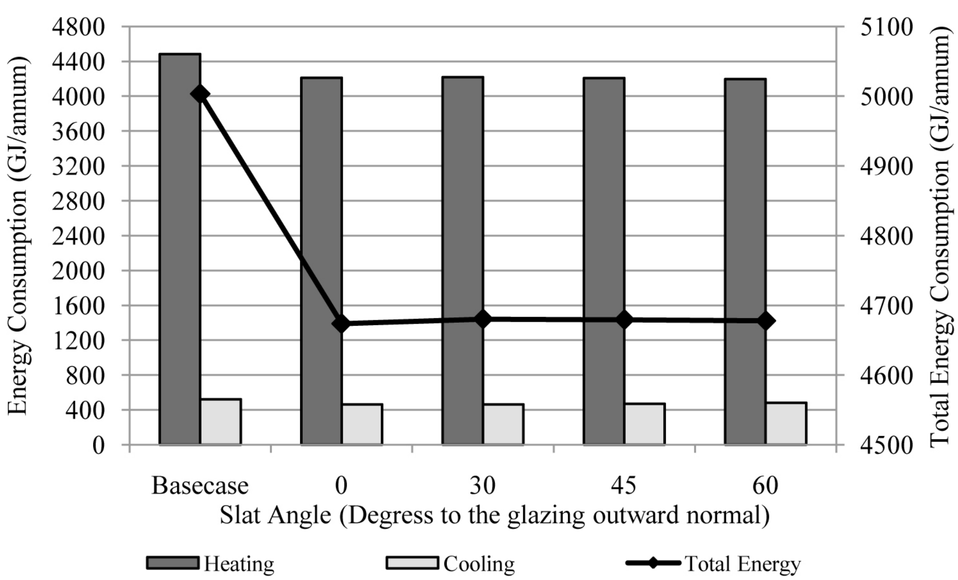
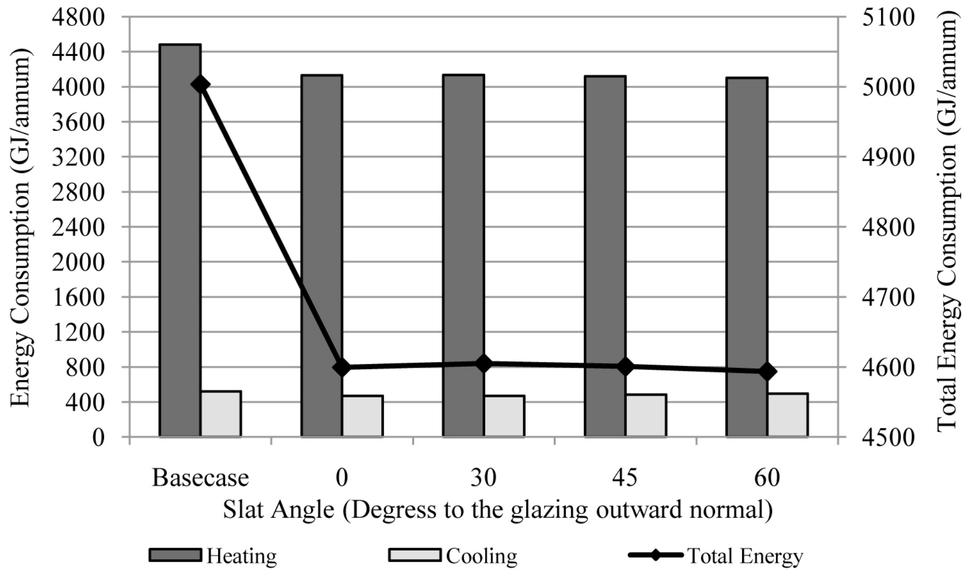


FIGURE 11. The effect of window shades with automatic control on space conditioning energy consumption.



absorb the solar heat during the day and contribute to the interior heat balance. As illustrated in Fig. 12, 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; as expected, cooling energy consumption on the other hand is increased by 6.2 %, or 32 GJ/annum (Fig. 12), leading to a decrease of merely 0.9 % for the total energy consumption (Fig. 13). The increase in cooling energy consumption with increasing absortpance is due to the increase in heat gain through the external walls throughout the year. During the summer, the dark surfaces effectively absorb the solar heat and contribute to the space's heat

FIGURE 12. Effects of solar absorptivity on heating and cooling energy consumption.

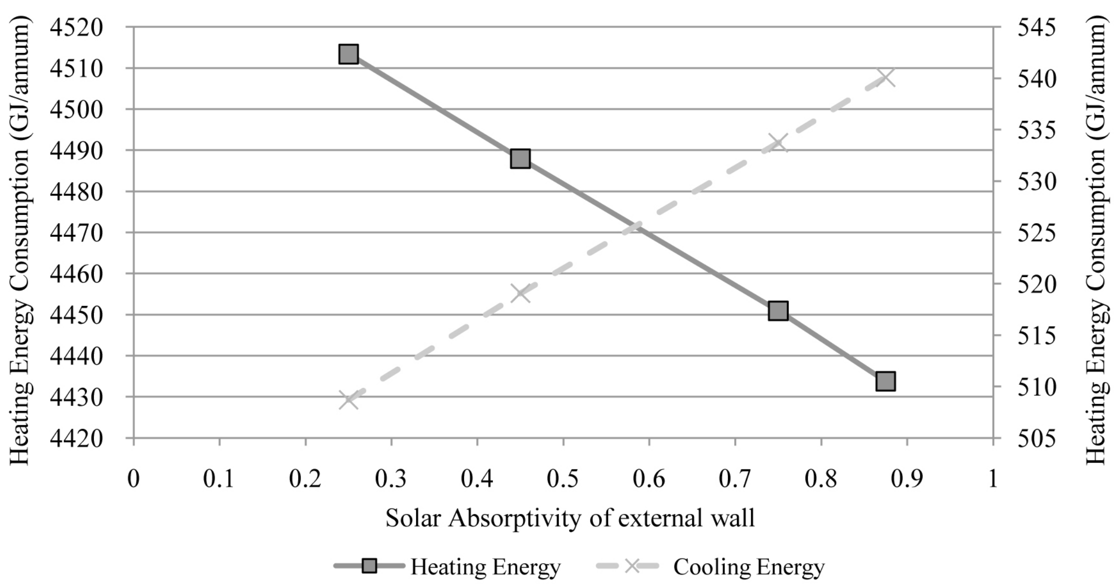
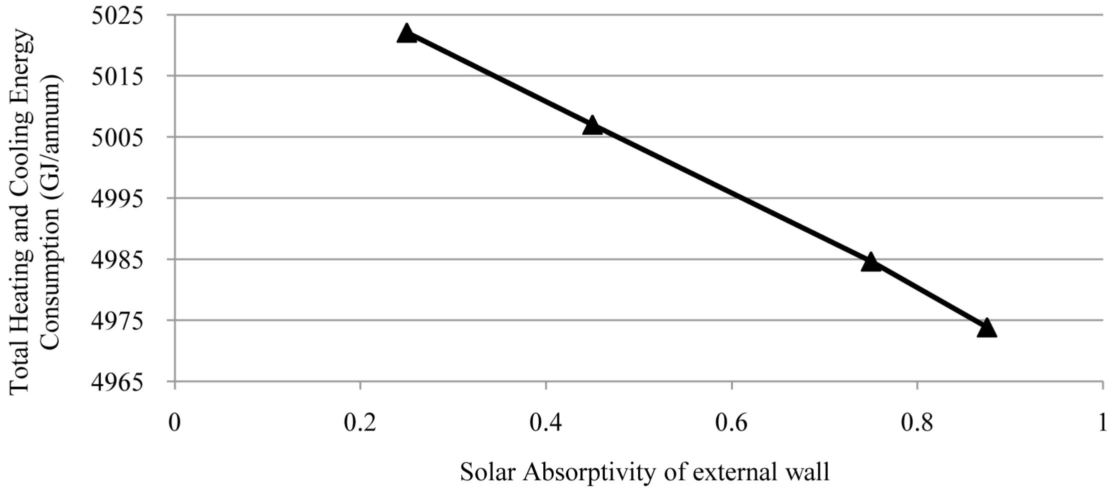


FIGURE 13. Effects of solar absorptivity on total heating and cooling energy consumption.



gain, whereas a lighter surface would not absorb as much solar heat and therefore lessen the amount of heat being transferred to the interior. 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. 14-15). 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. 14, 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. 15); the south-facing wall displays the steepest negative slope, followed by east-, west-, and north-facing walls.

FIGURE 14. Effect of solar absorptivity on heating load intensity with different orientations.

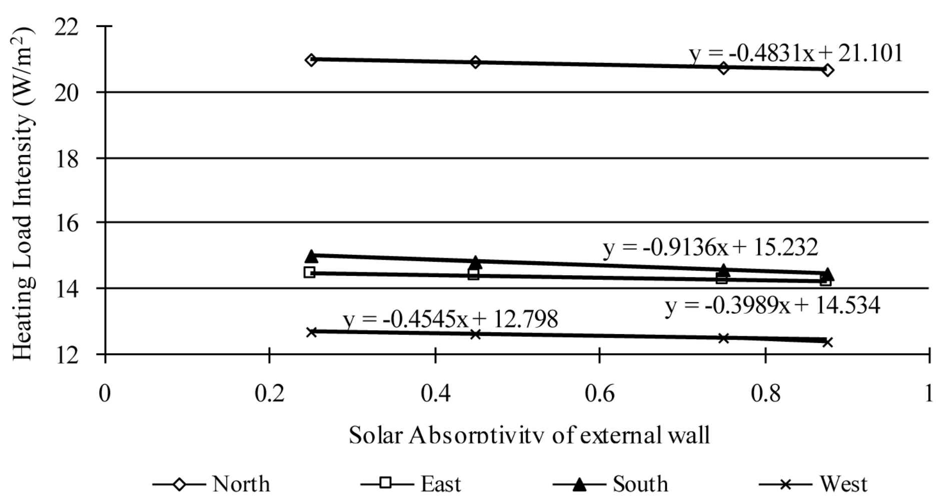
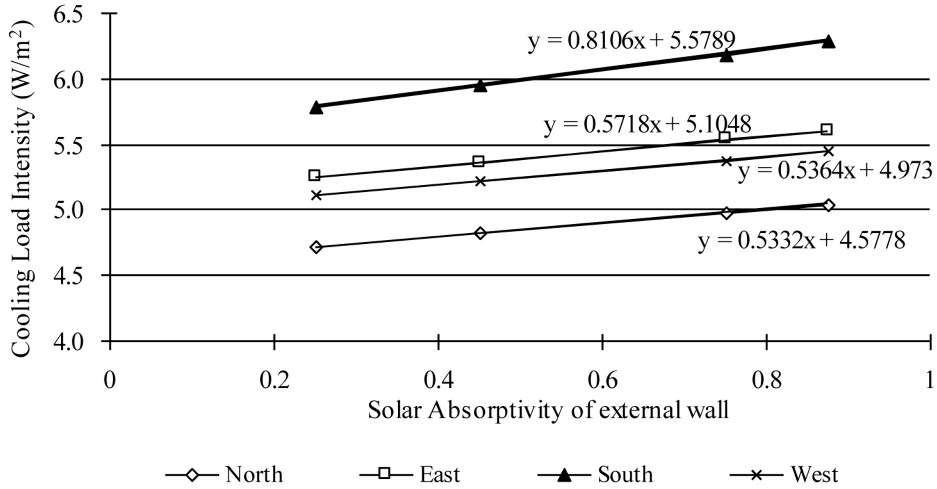


FIGURE 15. Effect of solar absorptivity on cooling load intensity with different orientations.

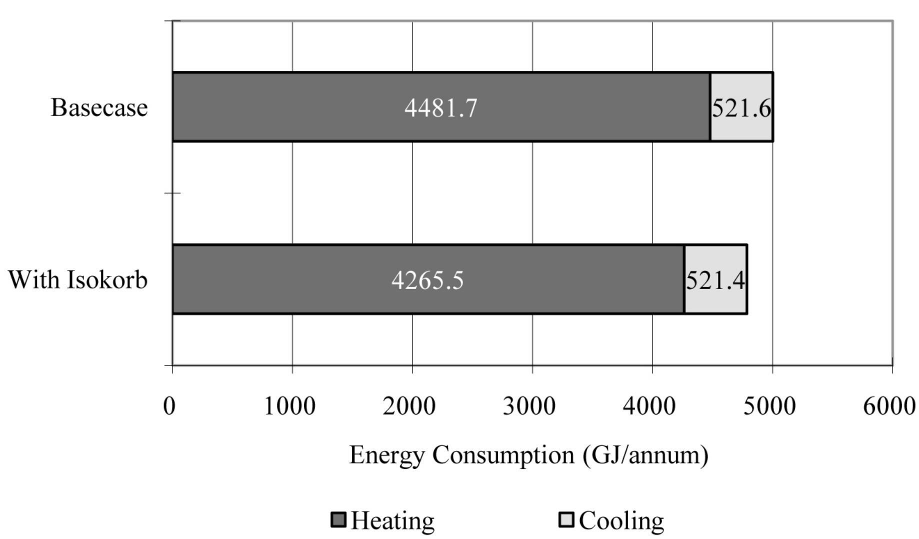


5.6. Thermal break system

A thermal break system used in mitigating the thermal bridge at the concrete to concrete connection of the free cantilever balconies was incorporated into the envelope design to reduce heating and cooling energy consumption of the building. The concrete to concrete connection of the free cantilever balconies creates a continuous path for heat conduction from interior to exterior. The total span of the balconies was approximated to be 932.15m for the entire building. The thermal break system in thermally separating the concrete to concrete connection of the free cantilever balconies to the interior slab was evaluated. The R value at the slab edge (between the slab on the inside and the balcony) was set to be R 13 (80mm of .035 W/(m*K)).

Fig. 16 illustrates the simulation results. As seen, the thermal break system is able to reduce the heating energy consumption of the building by 4.8%. On the other hand, cooling energy consumption remains constant.

FIGURE 16. Heating and cooling energy consumption with Isokorb system.



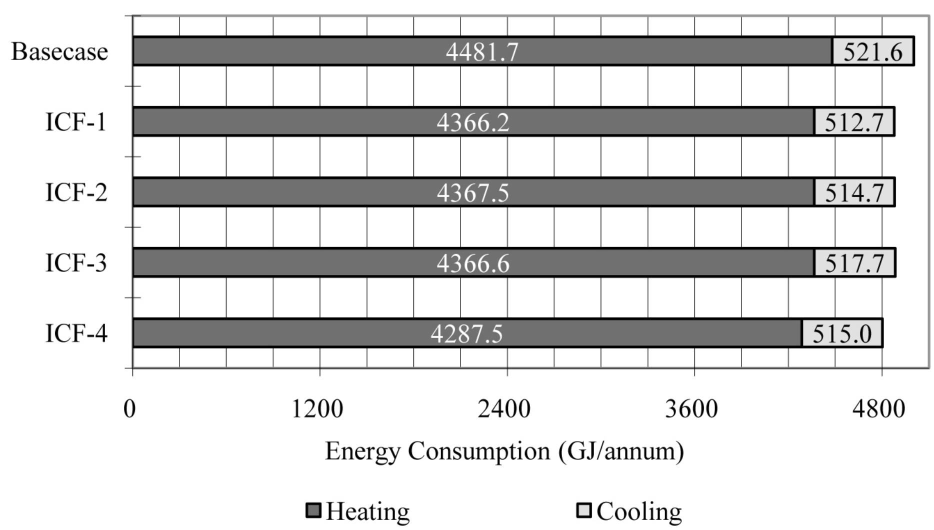
5.7. Insulated Concrete Forms

Four Insulated Concrete Form (ICF) configurations were investigated to determine their relative energy performance (Table 6). The chosen ICF systems all have a higher insulation value than the as-designed precast insulated concrete panels, which is currently at RSI 2.41 (R 13.7). As expected, in all four cases, heating energy consumption decreases as thermal resistance increases (Fig. 17). By incorporating ICF-1, -2, -3, and -4 into the building's exterior wall, heating energy consumption of the building would be reduced by approximately 2.6% for ICF-1, -2, an -3, and 4.3% for ICF-4; cooling energy consumption on the other hand is reduced by approximately 1.7% for ICF-1, 1.3% for ICF-2, 0.8% for ICF-3, and 1.3% for ICF-4. ICF-1 performs slightly better than ICF-2 and -3 as simulation results show that ICF-1 achieves the biggest reduction in both heating and cooling energy consumptions. All three configurations have the same R-value and material thickness and the difference in performance is due to the thermal capacitance of the external wall. However, the difference between the three configurations might be too small to conclude any significant savings with manipulating the configurations. The total energy consumption is reduced by approximately 2.4 % for ICF-1 to -3, and by 4.0% for ICF-4.

TABLE 6. Wall configurations under investigation.

Wall ID	Configuration (interior insulation + concrete + exterior insulation)	Thickness (mm)	RSI	R
ICF-1	25 + 200 + 75 mm	300	2.85	16.2
ICF-2	50 + 200 + 50 mm	300	2.85	16.2
ICF-3	75 + 200 + 25 mm	300	2.85	16.2
ICF-4	62.5 + 200 + 62.5 mm	325	3.47	19.7

FIGURE 17. Effects of ICF configurations on heating and cooling energy consumption.



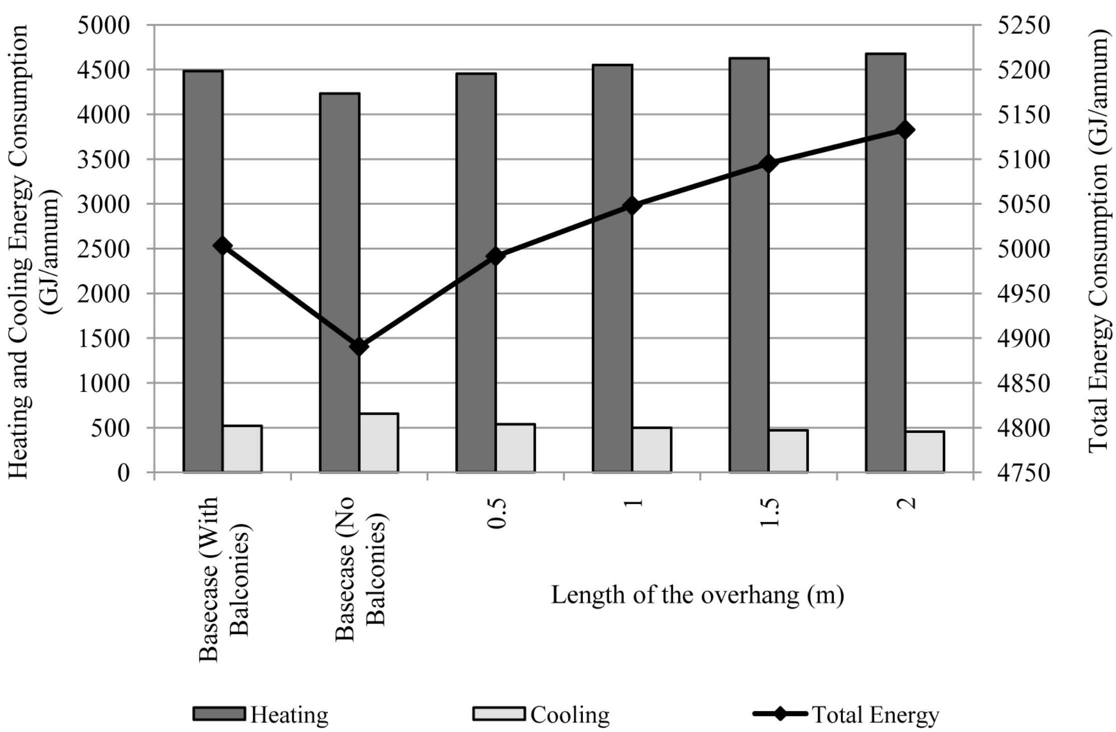
5.8. Overhang

The as-designed building consists of balcony structures that span approximately 52% of the building perimeter. These balcony structures extend 1.9 m from the exterior wall. To evaluate the effectiveness of the as-designed balconies in shading unwanted solar heat in the summer, simulation was performed on the building without the as-designed balconies. As well, a series of simulation was performed incorporating exterior overhang structures at 0.5m increments. Simulation results (Fig.18) show that although the as-designed balcony structures are able to reduce the cooling energy consumption by 20.6% when compared to the Basecase with no balconies, heating energy consumption is increased by 5.9% and the combination results in an increase of total energy consumption by 2.3%. Installing overhang structures can help reduce solar heat gain during cooling seasons. Reductions of 18.1% to 28.4% in cooling energy consumption are recorded; with 2m overhang structures achieving the largest reduction. However, as overhang structures are in place, the admittance of passive solar heat gain desired for heating seasons is affected and leads to an increase of heating energy consumption. An increase of 5.2% to 9.2% is recorded.

5.9. Window configurations

Perrson et al. (2006) studied the impact of window orientation to the space heating and cooling demand in Sweden and concluded that north-facing windows have the largest impact on space heating load, followed closely by east- and west-facing windows respectively. On the other hand, space cooling demand was impacted by west-facing windows the most, followed by east-, and south-facing windows respectively. Her study also found that the influence of

FIGURE 18. Effect of external window overhang structures on heating and cooling energy consumption.



east- and west- facing windows on space heating and cooling demand does not differ noticeably. Straube and Burnett (2005) illustrated that east- and west-facing windows receive 40% more solar heating than south-facing windows on July 21st at 45' north latitude (Toronto is at 43'40" north latitude). On the other hand, on January 21st, south-facing windows receive approximately 3.6 times the solar heating east- or west-facing windows receive, and 15 times the solar heating north-facing windows receive. Lechner (2009) illustrated that all orientation except south receive maximum solar radiation in summer.

Previous research on low-energy buildings with whole building analysis generally investigated the performance of installing the same glazing system in all orientations and neglected to study the potential benefits of installing different glazing systems in different orientations. From previous studies (Persson et al., 2006; Straube and Burnett, 2005; Lechner, 2009), six window configurations with four types of windows were evaluated in this paper. In Configuration 1, EnergyStar certified windows (SHGC: 0.44, U-value: 1.5W/m^{2}K) are used in north-facing walls only. In Configuration 2, in addition to using EnergyStar certified windows in north-facing walls, east-, and west- facing walls are also equipped with EnergyStar certified windows. Configuration 3 is same as Configuration 2, but with east-, and west- facing windows also equipped with high SHGC (0.568). In Configuration 4, south-facing walls are also equipped with EnergyStar certified windows. Configuration 5 is very similar to Configuration 4 but with south-facing windows also equipped with high SHGC. Configuration 6 aims to reduce unwanted solar heat gain during cooling seasons and uses spectrally selective windows in west-facing windows. The configurations are as summarized in Table 7.

The EnergyStar certified windows are Argon gas filled (6mm), double glazed units, consisting of outer pane of 10 mm thick clear glass and inner pane of 6mm Ti-R glass with low-E coating. DesignBuilder (DB) calculated the SHGC to be 0.44 and U-value was set to be 1.5 W/m^{2}K.The EnergyStar certified windows with high SHGC are Argon gas filled (13mm), double glazed units, consisting of outer pane of 6 mm thick clear glass with low-E coating and inner pane of 6 mm thick glass. DB calculated the SHGC to be 0.568 and U-value to be 1.5 W/m^{2}K. The spectrally selective windows are argon gas filled, double glazed units, consisting of outer pane of 6mm thick spectrally selective tinted glass and inner pane of 6mm thick clear glass. U-value and SHGC were calculated to be 1.34 W/m2K and 0.274. All windows are framed with PVC. The effect of replacing the existing window system with the above window

TABLE 7. Window configurations.

Configuration ID	North-facing		East-facing		South-facing		West-facing	
	U-value (W/m^{2}K)	SHGC	U-value (W/m^{2}K)	SHGC	U-value (W/m^{2}K)	SHGC	U-value (W/m^{2}K)	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

configurations was investigated (Fig. 19 & 20). As shown in Fig. 20, there exists a net heat loss through the glazing for Basecase and Configuration 1. Heat flow is calculated to be the difference of conduction heat loss and heat gain through the glazing system. 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. Net positive heat gains are resulted for Configuration 2 to 6 as solar heat gain through the glazing systems increases.

As the north-facing windows were replaced with EnergyStar certified windows from Basecase to Configuration 1, the heat loss through external glazing is reduced by 6.4% and solar gain through windows is varied decreased negligibly from Basecase to Configuration 1. This results in a reduction of 2.7% for heating energy consumption and a 1.1% increase for cooling energy 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. The amount of conductive heat loss through windows is approximately the same in north-facing and east- or west-facing windows (Lechner, 2009), and since the building is oriented such that the long sides faces east and west, replacing windows on the east and west walls would have a more pronounced impact on the heat balance. Similar to Configuration 1, the amount of solar heat gain through windows differs negligibly as better insulated windows are installed. As a result, heating and cooling energy 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 higher SHGC on the east- and west-facing windows, a significant increase of solar gain through the windows is recorded according to the simulation results. The amount of solar gain through the windows is increased by approximately 20.4% throughout the year. The amount of heat loss through glazing on the other hand is reduced by approximately 26.9% when compared to Basecase. The combination of decreased glazing heat loss and increased solar heat gain through glazing results in a decrease of heating energy consumption of 17.0% from Basecase. During the summer, the increased

FIGURE 19. Heat gain (loss) and transmitted solar energy with varying window configurations.

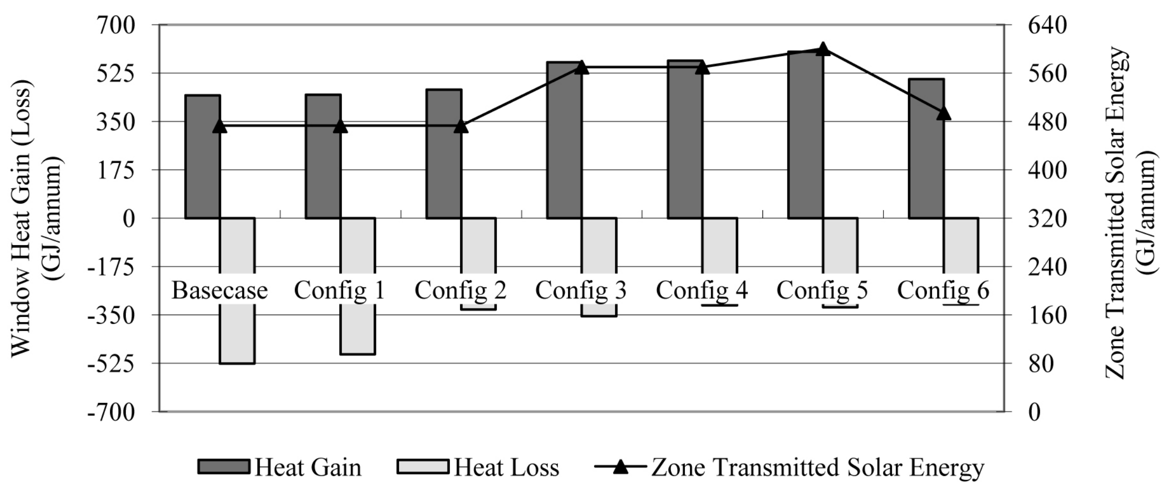
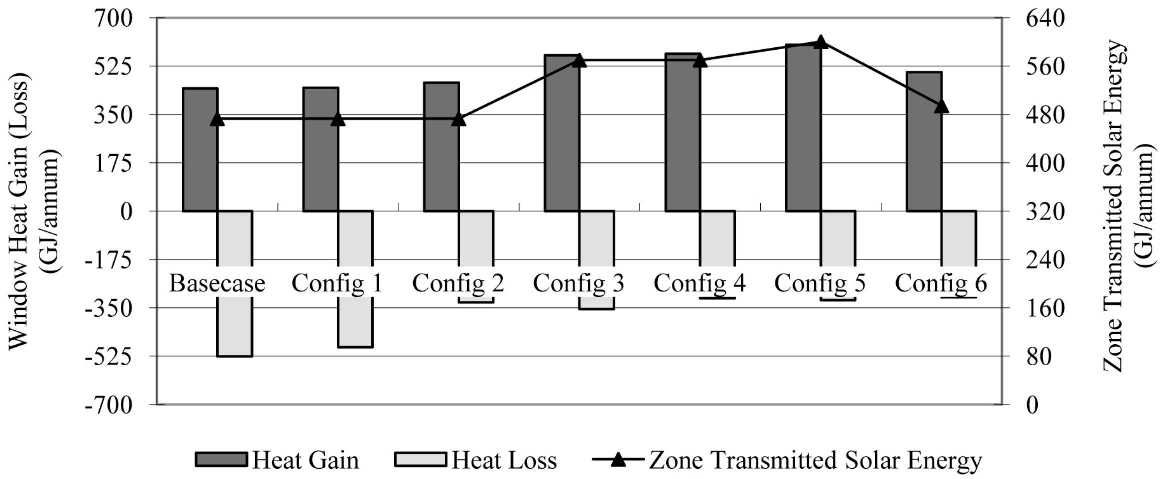


FIGURE 20. Effects of window configurations on heating and cooling energy consumption.



amount of solar gain causes the cooling energy consumption to increase significantly by 12.5%. While the high solar heat gain glazing system is effective in allowing more passive solar heat into the space during winter heating seasons, the lack of effective shading devices causes the cooling energy consumption to be increased significantly when compared to Basecase. This leads to a reduction of total energy consumption by 13.9% when compared to Basecase.

Configuration 4 is similar to Configuration 3, with south-facing windows also be replaced with EnergyStar certified windows. The impact of this upgrade 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. Generally, when designing passive buildings, a common technique is to place large glazed areas oriented to the south to maximize solar heat gain during the winter. 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 of the reduction of heating energy consumption and increase of cooling energy consumption 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. Similar to Configuration 5, north-, east-, and south- facing walls are installed with energy-efficient windows. East- and south-facing windows are still equipped with a higher solar heat gain coefficient. 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.

The benefits of installing more advanced windows on different orientations are made clear with the above discussions. The decision on which configuration to incorporate is a trade-off between cost and performance. Fig. 20 illustrates the heating and cooling energy consumption reduction for all configurations. Although Configuration 5 achieves the biggest reduction in heating and cooling energy consumption at 17.1%, one can argue that the additional investment might not justify the marginal reduction.

6. CONCLUSION AND FUTURE WORK

This paper describes the investigations performed on the building energy performance of a 12-storey apartment building in Toronto as part of an IDP. During the preliminary design phase, detailed building energy analysis was conducted with computer simulation programs to evaluate the performances of different low-energy envelope design strategies. The performance of buildings is a complex issue that involves the interaction between active and passive systems, building operation, and the environmental factors. Design tools that can take all the above aspects into account are essential in generating high-performance building designs. Simulation provided an effective way of evaluating the performances of different designs virtually, with relatively small time and monetary investments.

Although sophisticated programs like EnergyPlus can usually better represent real-world complexities, architects and design team members have found that some of these programs are complex in nature and are very difficult to use. Design team members are usually overwhelmed by the steep learning curve and the amount of time needed to establish the model. As a result, design teams generally employ less complex simulation programs such as eQuest, HAP, and TRACE, as they provide dynamic default values for some of the parameters and less versatile interface to greatly reduce the complexity of the input requirements. However, with the increasing demand of incorporating new and novel technologies, strategies, and materials to building design, less complex simulation programs might not be capable of evaluating some of the more complex design strategies. As building projects are usually characterized by tight schedules and budgets, collaboration between academia and industry provides one of the solutions to this challenge. Researchers from academia can offer their resources and expertise in simulation to overcome the existing barrier of employing more versatile and accurate programs as standard practises in the industry. As well, more in-depth literature reviews can be conducted by researchers in academia to enable thorough investigations of different energy conserving strategies.

As part of the IDP, members of the design team made use of simulation results and made changes to the building design accordingly. The process in identifying and evaluating different strategies resulted in an iterative process where design ideas and concepts were exchanged between design team members. Ideas put forward were applied to the simulation model for performances evaluations, and modifications to the design proceeded as applicable. On top of illustrating the potentials in reducing energy demand for new constructions, this project also provided insights into various low-energy envelope strategies. Simulation results show that cooling energy consumption 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 heating and cooling. On the other hand, manipulating the thermal mass of the exterior wall does not yield significant reductions in either heating or cooling energy consumption. The findings on exterior wall R-value and thermal mass 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. Subsequently, the air-tightness level of the building affects the heating energy consumption significantly by up to 35.5% with air-tightness reduced from 0.4 ACH to 0.1 ACH. The impact of improving the air-tightness of the building on the heating energy consumption of the building is far more superior to many of the strategies described in this report, and thus it might be worthwhile for current building certification programs to integrate the impacts of improving air-tightness into their accreditation programs so as to encourage better building practises and increase energy efficiency of buildings.

This simulation indicates that there is a large potential to decrease the energy consumption in this apartment by employing certain envelope improvements discussed in this paper. It can be suggested that when designing buildings, it is necessary to perform energy simulation to evaluate the energy savings of potential improvements to the envelope system. 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 analyses and access the environmental impacts of the building over its whole life cycle. Also, post-occupancy evaluation (POE) should be carried out to help identify if design intents, specifically those related to thermal comfort and energy consumptions, are met. As well, there might be synergy or antagonism with combining the strategies described in this paper, the performance of different combinations will be subjected to future studies. Lastly, future research can focus on the development of adaptive control schemes for optimizing the control of the exterior window shade systems, or even mechanical equipments such as chillers, boiler, furnace, pump and fan in the generation plant of any HVAC system of high rise buildings. These control schemes have a potential to increase the energy efficiency of the building heating and cooling systems and improve the thermal comfort for the occupants and some examples are shown in Jassar et al. (2008, 2009), and Liao & Dexter (2003).

ACKNOWLEDGEMENT

The work presented in this paper is partially funded by National Sciences and Engineering Research Council of Canada (NSERC) through Discovery Grant (project reference numbers: 313375-07) and MITACS ACCELERATE Internship program. Research was carried out in conjunction with an industry partner, Trow Associates and is carried out at Ryerson University, Toronto, Canada. The support of these organizations is gratefully acknowledged.

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