CONTROL OF WINDOW THERMAL INSULATION RESPONSE AND ENERGY SAVINGS

by

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Abstract

A definite requirement of the building envelope is to separate the natural environment from the indoor environment. Energy is one component of the environment that we sometimes wish to capture, harness, or reject. How can these actions be best performed to yield passive benefits such as solar heating or shading?

This research focuses on control of solar radiation, and the role windows play as transfer medium between indoor and outdoor environments. A novel concept for passively controlling solar thermal energy input, and building thermal energy output with the use of operable insulation is investigated during the heating season.

This is done through a combination of finite element mathematical modeling using COMSOL multiphysics software (heat transfer module), field performance testing, and theoretical design/modeling for validation of this concept. Modeling and field testing revealed an energy imbalance attributed to unpredictable solar gains and spectrally dependent emissivity of materials. Simulation results of the concept reveal improvements that translate to reduced heat flux losses as compared to the tested and simulated normal static, or more commonly used daily-cycle systems.

Acknowledgements

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Thanks goes to my team, classroom and studio peers, and colleagues at EnergySavers as well. I hope our projects and discussions assist you in your endeavours as they have in mine.

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Terminology and Abbreviations

After-market: Referring to a component added after construction of a home is complete

Albedo: Term for reflection coefficient often used in radiation problems

Building thermal energy balance: Referring to the thermal equilibrium based on losses and gains from the transport mechanisms of conduction, convection, and radiation

Building Envelope: AKA the 'skin' of the building. It is responsible for environmental separation, partially responsible for maintenance of occupant comfort and is often non-structural

Dressing/Treatment: Referring to additional components added to a window assembly for energetic and/or aesthetic purposes

Fenestration: A building component that penetrates the building envelope (i.e. a skylight, window, door etc.)

Flame Spread Rating: A measure of 0-100 (on a relative material-based scale) of a material's flame spread rate when exposed to an ignition source

Glazing: Environmental separator that allows for transmission of light in one or more parts of the electromagnetic spectrum (usually glass or plastic)

Greater Toronto Area (GTA): Geographic area consisting of the city of Toronto and surrounding municipalities

Heat Flux: Heat flowing through a unit area of material over time (positive values usually indicate a loss of heat)

Irradiance: Instantaneous incident energy on a surface

Movable/Operable Insulation (OI): An insulating component that can be translated for the purpose of altering thermal resistance of the overall assembly

Multi-Unit Residential Building (MURB): A building type consisting of a number of separate dwellings (i.e. an apartment)

Passive Control: Refers to a control that is actuated by sensors that rely on ambient/environmental inputs

Photovoltaic (PV): Referring to a device capable of transforming solar radiation into electricity through the photovoltaic effect

Pyranometer: A sensor that produces a voltage for measurement based on temperature differential induced by incident solar radiation energy

Sol-Air Temperature: A simplification equating the sum of environmental changes to a single surface temperature (often used for simplification of cooling load calculations)

Smoked Developed Rating: A measure of 0-100 of the concentration of smoke emitted from a material when burning (based on the same relative scale as the flame spread rating test)

Thermal Resistance (U/R value): A material property influencing the rate of heat flux

Thermocouple: A sensor that produces a voltage for measurement based on temperature differential

Thermo-graphic/Thermal Imaging: A method of producing images using the infrared spectrum, for the purpose of thermal visualization

View Factor: A concept used in modeling of radiation problems, relating to the shading/masking influences of geometry on radiation propagation

Window: An exterior wall opening assembly component consisting of glazing, frame and other air-sealing components

Window Opening (WO): Term for a building envelope opening reserved for insertion of fenestration

Window-Room Plane: A fictitious surface used for measurement of total heat flux in isolation; independent of room size and other construction variations

Variables and Units

Density (ρ) – kg/m^3

Heat Flux (q) – W/m^2

Irradiance (G) – W/m^2

Specific Heat Capacity (Cp) – $J/K \bullet kg$

Surface Emissivity/Solar Absorptivity (ε) – $ratio\ 0-1$

Temperature (T) - $°C$

Thermal Conductivity (k)- $W/m \bullet K$

Thermal Resistance – $1/k$

Velocity (V) – m/s

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1. Introduction

In developed nations with a defined heating season; building energy use accounts for roughly 40% of all consumed energy, and roughly 40% of this energy is consumed by space heating, on an annual basis. This percentage increases for climates with longer heating seasons and more extreme winters such as Canada, Russia, and northern Europe [IEA 2012, Ch. 1].

In a cold climate, energy in the form of heat escapes through the building envelope (walls, roof etc). Windows and other glazed elements are a particularly large source of heat energy losses as compared to walls or rooves due to their low thermal resistance.

Glazing elements cannot be eliminated however as they are an important component of all buildings and required by most modern building codes. They can serve the functions of gaining valuable solar heat and daylight, venting heated air in the cooling season as well as serving as a visual connection to the environment.

Thus the problem: How can these functions be fulfilled while improving control of thermal energy transmission through windows?

1.1 Background

Unfortunately, after the building envelope and possible passive energy design strategies employed in the design phase, designers and occupants turn to active heating and cooling systems to regulate the indoor environment. Examples of active systems – many of which rely on power from a non-renewable energy source – include: natural gas furnaces, electric baseboard heaters, and refrigerant air conditioners. These systems are seen as the primary lines of defence to combat changes to the thermal environment over time. Many of these changes are predictable based on historical data, i.e. daily or seasonal temperature swings. However, most air conditioning systems are designed and sized according to over-estimated loads. They should logically then, only be responsible for these extremities in building loading in the heating or cooling seasons. There are energy and financial consequences associated with relying on active systems to meet dynamic heating and cooling loads. These are validated by and addressed in part, through legislation (i.e. local building codes) as well as a number of standards that are meant to respond to recent market forces (such as the LEED rating program). This research attempts to translate more of the defensive responsibility of maintaining a comfortable indoor thermal environment from active (energy consuming) heating systems, to the building envelope itself. The purpose of this study is to provide a means for improving the level of control regarding energy transmission through windows with operable insulation (OI) in order to optimize the whole building energy balance and window-adjacent occupant comfort, whilst maintaining desired visual performance.

1.2 The Problem

There are two control systems in common use for operable insulation; each with their own specific challenges and limitations. They are manual controlled, and static operable insulation systems. The application of night-time and other timely manual controls to operable insulation (OI) is an excellent start to the problem of window heat loss; proven in the literature to improve upon building thermal losses more than 50% of the time in the heating season [Liu 2012, 432-443].

There is an inherent drawback with manual control of systems however; in order for any OI system to be effective, it needs to be appropriately operated. Human error (read *forgetfulness/laziness*) is a notorious opponent to efficiency of systems relying on manual operation and should be minimized or altogether eliminated. A static system also has an inherent limitation; that it is permanent. While this ensures that heat loss through the window is limited, it affects normal desirable window functionality such as admitting daylight, solar radiation and visual information.

The building energy balance is constantly being altered by changes in local weather, as well as solar exposure, that (especially for non-south orientations) is limited by the sun's path to certain times of the day. This signifies an opportunity for a day-time control to optimize the daily efficiency of an OI system. Consider the case of a cold, clear winter day; the incoming solar radiation energy has the potential to contribute heat in an amount greater than the savings provided by the OI. However, cloud cover and other shading masks alter this incoming energy unpredictably throughout the day, by as much as 23% for clouds and 100% for opaque objects, such as trees [IEA 2011, Ch. 2]. Juggling manual control of all windows with OI in a home over time, against these changing conditions, is a task the average homeowner could not hope to keep up with day after day.

The scope of this research extends the current state of the art of timely manual control to an automatic environmentally responsive control that automatically leverages solar gains against heat losses over 24 hours, to optimize the building energy balance.

2. Literature Review

2.1 Windows and Solar Design

Historically, windows have not changed much in terms of functional requirements. They still admit light and visual information, and act as environmental separators as originally intended. They also were and remain an expensive component of the building envelope. “Glass was an expensive commodity in the 1580s, with a lot of skill and energy required to make it” and “was put into buildings as a demonstration of wealth… 100 years later, Louis XIV of France sponsored a technological drive to invent glass strong enough to be located in carriage windows” [Wigginton 2007, Ch. 2]. After this cross-disciplinary engineering endeavour eventually produced more durable window glass, its use in buildings became more affordable and widespread.

The modern window is a relatively expensive envelope component (though not to the point where exclusion from buildings is considered), requiring periodic replacement. The modern window still acts as environmental separator and visual connector, but has additional functions, both designed and inherent. Most modern window assemblies can be operated to allow for ventilation/exhaustion of indoor air. They are also an envelope component that admits solar radiation. Certain window manufacturers will apply films or coatings to various surfaces of the window that will allow for increased transmission/reflection of radiation within a desirable band or portion of the electromagnetic spectrum. This produces various results that can positively impact building energy use depending on the local climate. These include greater overall energy transmission or reflection and solar heat gain/rejection, respectively. [EWC 2011].

There are numerous papers concerned with passive solar design for buildings. There is a wide range of research within the subject including: passive solar heating and lighting strategies, site-specific optimization and comparisons, building integration of active collection technologies (such as Solar Photovoltaics or Thermal), active solar cooling strategies (such as , and more. Site specific optimization is often concerned with the building envelope as a whole, while heating and lighting strategies often focus on single building components or building façades (i.e. orientations).

This research is associated with a passive solar heating strategy (and lighting by proxy), with an element of site specificity. Passive systems share common elements; a collection device, storage medium and distribution method (heat transfer strategy). The primary methods for harnessing solar heat gain passively are direct, indirect and isolated gain. Passive thermal collector designs in buildings include use of thermal mass for timely storage and re-radiation, such as trombe walls. Windows themselves can be classified as a type of direct/indirect gain collector as they are an aperture for radiation. The interior building construction components and air act as storage medium and distribution channel respectively, through the processes of re-radiation and convection of the indoor air. Direct gain systems using windows have the advantage of already being effectively incorporated in constructions with appropriate window design. Inappropriate window designs exist however, and they can suffer from symptoms of poor control; such as overheating spaces and producing excess glare on surfaces [NCDC 1999]. One can appreciate then the fact that window interaction with solar energy makes up a large portion of the passive solar design research base.

A direct gain system relies on direct solar radiation to capture heat (see Figure 2.1 adapted from the work of Anderson and Michal (1980, 61) on the next page)

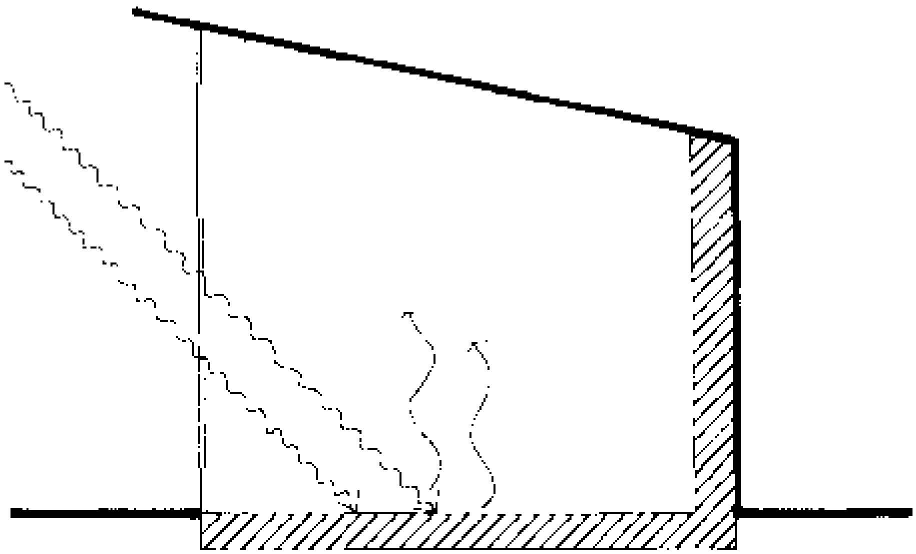

Figure 2.1 Basic Direct Gain System

Radiation emits from all bodies at some frequency. It is largely a function of their temperature, but also is associated with a property known as surface emissivity. Larger/more energetic objects like the sun emit radiation of a large magnitude and across a wide spectrum of frequencies.

A further merit to using a window as a direct gain system is that use of a transparent medium such as glass allows for some containment of heat (either generated from the building/occupants or gained from the sun) as it is reradiated at a lower frequency by the far less energetic building components or interior air mass. This is achieved because window glass experiences a large change in emissivity depending on the wavelength of incident radiation [Frei Dec. 2013]. This is known as a spectrally dependent property and is also affected by the temperature of the material.

2.2 Operable Window Insulation

Insulation is typically a fixed component within the building envelope. It needs to remain continuous and unbroken to be an effective insulator. An insulating material must also have a relatively low thermal conductivity and limit air movement. Simply put, this means that effective insulators lower the rate of heat loss as compared to poor insulators.

Windows and other wall penetrations have poor insulating properties as compared to the building envelope. This makes them the envelope's thermal weak point that has required extra mitigation efforts since the invention of window glass. Pragmatic methods have been as simple as hanging curtains, quilts or applying other dressings to the window to limit heat loss and these are all forms of OI. They fall into two broad categories; interior and exterior systems. Exterior systems often suffer from a lack of control as they are less easily accessible than an interior system, while interior systems often experience more condensation issues [Langdon 1980, Ch. 1]. Systems can become quite complex when they also incorporate storage media for delayed re-radiation, such as water drums, rock beds or roof ponds (see Figure 2.2 for an example adapted from the work of Anderson and Michal (1980, 67).

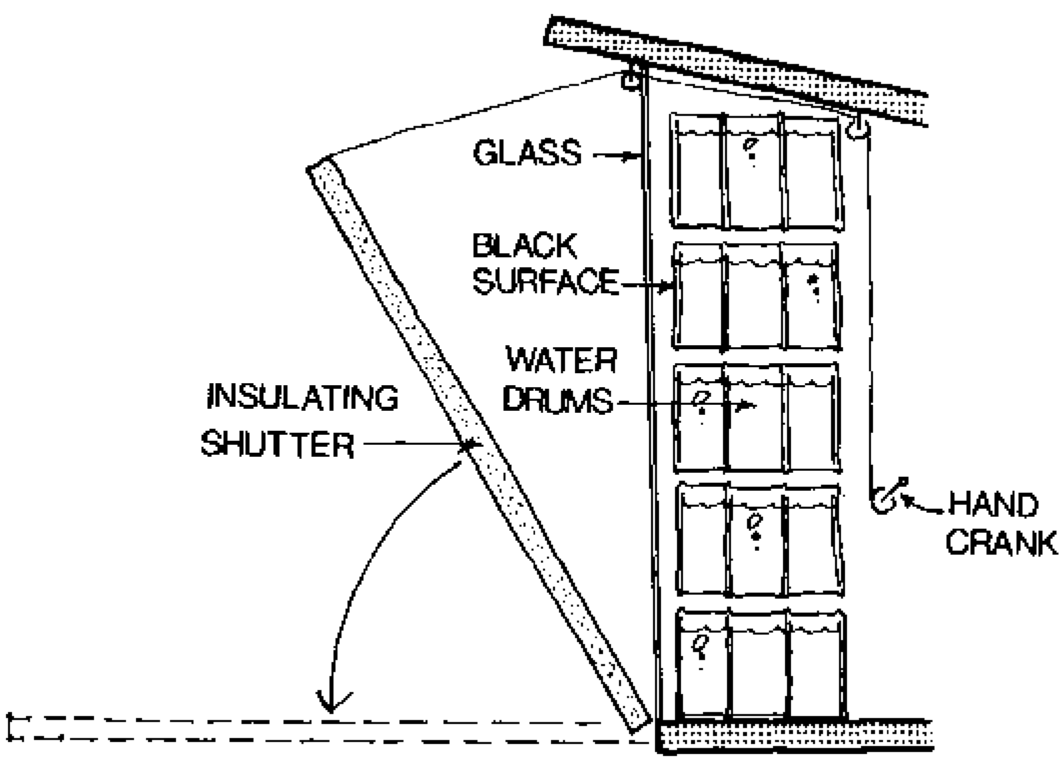

Figure 2.2 Hand Operating Insulating Shutter with Thermal Storage

The state of the art is transparent or translucent insulation materials (TIMs) that allows for some transmission of visible light while providing additional insulating value. These would be classified as non-view systems however, as views are often distorted due to the additional material. Presently, application of this technology to existing windows is not possible as there are elevated concerns with overheating and breakage [Peuportier 2011]. In addition, such systems are often not feasible as aerogel and other clear insulating materials are recent innovations that are more expensive to produce [Kaushika 2003, 317-351].

OI is an effective concept for timely heat savings, but not a novel one. It has been used pragmatically throughout cold climates for much of history. Despite this fact, there are inherent drawbacks to most operable insulating methods that have not been addressed even to this day. This is due to traditional construction and control methods. The main drawback that this paper addresses, is that these systems are often in static configurations and require manual user operation. This can lead to a number of detriments, including unventilated window overheating – a cause for potential damage, and more importantly it forms some restriction to passive building heating from potential solar heat gains through the glazing.

2.3 Experimentation and Mathematical Modelling

Literature surrounding the thermal performance of glazed fenestration in buildings is ample. Modelling methods are numerous but the most complete mathematical models approach the problem from the perspective of thermal energy transfer and computational fluid dynamics (CFD) in two or three dimensions. This is a necessity as these models can be very large, and computationally intense to solve, especially in models considering radiation on top of transient conduction and convection effects. Papers such as Wong's [2003, Ch. 2] validate the methodological approach of thermography (infrared imaging) for determining fenestration surface temperature and providing effective visual feedback to problems. Additional experimental research often uses locally applied thermocouples. Surface temperature and its differential over various components is a main parameter for determining thermal performance of any construction assembly. This research employs both methods for the experimental component (with reasoning outlined in the methodology section below). Regardless of modelling or methodological approach, these studies have identified thermal resistance deficiencies of some form associated with even the most so-called “energy-efficient” designs; such as triple-pane evacuated/gas-filled windows.

The work of Muneer [2004, Ch. 1, 4-6, 8] provided direction for creation of accurate solar radiation models. He provides data and modeling methods to account for the main components of radiation reaching building surfaces with corrections for a number of intermediate factors; such as view factor calculation, glazing transmission characteristics and ground albedo. He also provides explanation for the data creation process used by pyranometers, which helps to clarify what intermediate factors need to be incorporated into the mathematical model. Regarding our specific modeling technique, a number of papers and tutorials were reviewed. The solar/radiation components were modeled closely after papers that simulate energy performance of a number of solar collection technologies. One such paper by Motte et al [2011], deals with a COMSOL simulation problem involving a fluid-based thermal solar collector. His glazed-over cavity with a fluid adjacent collection layer, mimicked our problem in terms of layer arrangement and heat transfer methods.

The theoretical and experimental analysis of conventional after-market window treatments has also been performed. They fall into two broad categories of either possessing thermal or non-thermal energetic functions. Papers by Shahid [2005, 836-843] and others explore the parameters associated with convective and conductive thermal energy transfer around common shading devices such as venetian-style blinds and shutters. CFD software is often used as the basis for 2D mathematical models in these studies. Results include a small reduction in thermal losses due to the blinds creating a series of small convective loops in between slats and adjacent to the window.

This study aims to provide a means for control and optimization of the *building energy balance* through building glazing elements. This means that there is a functional requirement of encouraging or limiting solar gains and building heat loss dependant on the energetic relationship between indoor and outdoor environment. There is considerable research regarding control and optimization of novel façade designs or additions that affect solar parameters and contribute to the building energy balance. Much of this research however, considers only a single parameter such as daylight or solar heating – or conversely – shading and cooling. Newsham and Arsenal [2008, 143-163] constructed a room-customized automatic shading system based on a modified light level profile sourced from a cell-phone camera. Results showed a greater degree of optimal whole-room daylight exhibited over various conditions as compared to more traditional automatic systems based on irradiance sensors at one location.

Park [2003] developed an optimally controlled smart façade based on an occupant responsive control system to leverage the demands of energy efficiency, and visual (daylight) and thermal comfort. The mathematical model was developed using a lumped calibrated method and the system relies on active control of its shading/insulating elements to meet demands. Control is separated into energy saving, visual comfort and thermal comfort utilities. Hansanuwat [2010] engaged in similar work but focused on the practical application of a system tailored to curtain-walled office buildings and differed in his control scheme. The system consisted of an overhang-louver element meant to adapt primarily to lighting conditions. Liu [2012, 432-443] developed a methodology for calculating thermal (U value) and bodily comfort performance (based on internal glazing surface temperature at close proximity) of night-time insulation for new constructions. Results were validated by standardized testing of a full-scale mock-up in a test facility and showed marked improvements. Another research work that focuses on OI systems has been performed by Alsaad. The research deals with manually controlled night-time insulation, applied to an institutional building. Alsaad's study showed good results similar to Liu's and also considered financial feasibility of implementing OI. He concluded that a design change from Aerogel to XPS panels would yield a reduction in payback period from nearly 90 year to about 3 years based on heating energy savings vs. the initial capital investment [Alsaad 2014, 79].

This area of research provides the basis for realistic modeling as well as some direction for design of the static system and the methodology for experimentation. It also reveals the knowledge gap and present limitations associated with control of OI and kinetic façade elements.

2.4 Case Studies

The Cold Climate Housing Research Centre [CCHRC 2011] conducted a review of built cases incorporating various aftermarket glazing thermal-improvement methods (such as OI systems, curtains and storm shutters) throughout Alaska. In addition to insulating value, other parameters were investigated; such as condensation potential and ease of installation. Other systems under study focused only on limiting thermal losses with the use of a radiant barrier, such as reflective and shrink-wrap films. These systems which can be classified as 'facing materials' provide little insulating value based on their materials' thermal resistance properties, but have other means of influencing heat loss (namely reflection of radiation) [Holladay 2010], which in the CCHRC study, unfortunately went unmeasured. Therefore, they were the bottom of the group when considering raw thermal improvement, but have other benefits such as limited profiles. All systems were static or required manual operation. The majority of these systems were constructed by the homeowners themselves, with little attention given to proper air-sealing or interaction with glazing functionality. Results include a modeled range of thermal resistance value improvements (center of glass measurements) of 55-692% for interior systems, 51-523% for exterior systems and 24-38% for radiant barriers.

Anderson and Michal's [1978, 57-100] research presents a number of built case studies and conceptual systems focused on passive solar heating and storage such as home-attached greenhouses, trombe walls, thermo-siphoning rock beds, and more. They offer a number of categorizations for the designs and systems including grouping them by end use (i.e. space heating, water heating, space cooling) and level of building integration or application potential. They determined that passive designs when properly applied, perform comparably to conventional construction but with additional energetic benefits that require no active energy inputs and often a lower frequency of required maintenance. Unfortunately, there is little quantitative assessment throughout this work and concepts of physical interaction are illustrated with lines and arrows. Furthermore, there is a lack of practical application knowledge for the multitude of design options they present.

Other design options with more practical applications for existing buildings is presented by Langdon [1980, Ch. 1-5] and Shurcliff [1980]. Their design work along with the reviewed, built, case studies form the basis for the design of the static prototype to experiment with under the GTA's climatic conditions.

2.5 Development/Diffusion

The actively and passively controlled construction component is becoming more commonplace as a design option for energy efficient buildings. The collection of works documented by el-Khoury et al. [2012, Ch. 4] is evidence of this shift. Development of environmentally responsive construction components is a relatively young area of research. Ever since engineers started bringing computing power into the physical environment, the notion of environmentally informed actions has been evolving – particularly in the built environment. "A stable system can exist only theoretically." Nowadays, building technology is somewhere in the metastable area. The case of an unstable system responds to dynamic conditions and user demands. This responsiveness can be achieved in the short term by "changing the envelope and over the long term by changing the properties of materials."

[Krainer 2007, 57-67]. See the following graph (Figure 2.3) adapted by Roaf [Nicol 1999, 169-170] for an explanation of control schemes (adaptive opportunities) and their potential impact on human comfort stress.

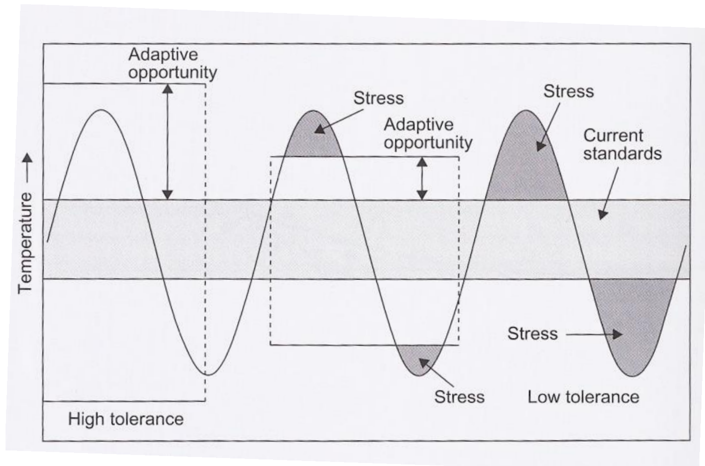

Figure 2.3 – Adaptive Opportunities and Occupant Comfort

The research of Nicol and McCartney reveals that the mere existence of a control does not mean it is used successfully. Passively controlled components are the next phase of regulation of the indoor environment, eliminating the obstacle of control use.

Constructor and building owner decision making psychology (described in detail in the significance section at the end of this paper) has been considered. Construction-technology diffusion is the subject area that best sums up this design consideration vs. usage phenomenon and not only applies to selection of a technology for use, but also the use over time of that particular technology; another difficulty associated with manual control.

It is a broad category of research and much of the current research focuses on ICT (information and communication technology) such as project management software, but there are some papers which deal with innovative construction materials and/or methods such as those of McCoy et al. [2010, 222-243] or Toole [2001, 107-114]. McCoy attempts to quantify diffusion parameters of a technology through a builder's practices survey and developed a tool for development likelihood based on a concurrent commercialization (CC) index at various thresholds. In certain cases, successfully adopted products had a high CC index and were contrary to other traditional indicators of market adoption (such as mitigating risk or industry best-practices).

Additional qualitative factors such as occupant reception to aesthetics and the mental shift from traditional window treatment operation also need to be considered. A number of architectural sources have documented the human impact of glazing as part of a building's solar design strategy. A paper published by Boyce [2009] highlights the unique ability of windows to provide a visual transition between interior and exterior environments. A number of other papers also confirm their importance to human health, via access to natural daylight sources when occupying indoor spaces. It is therefore prudent in this research to design a system that can preserve the current functions of a window.

Human interaction with the thermal environment is another qualitative consideration. The passively controlled system will be changing in form periodically, thereby providing the occupant with visual information that complements the changes to the thermal environment. This addresses a concept that Heschong refers to as "thermal delight" which has important implications regarding energy use; both from an engineer/designer's standpoint as well as that of homeowners and building occupants. While much of this research is background and more at home in the realm of psychology, it aptly describes the average North American occupant's behaviour with regard to thermal energy. "Continued pursuit of and exposure to a thermal steady state across time, and a thermal equilibrium across space, is unnatural and therefore requires a great deal of effort, and energy to maintain". Active systems are a necessity, yet their components are often hidden from direct view. She posits that for one to enjoy or even be conscious of being warmed or cooled it helps to have awareness of the process [1979, Ch. 2-3]. This is a further qualitative and possible educational benefit to use of an OI system that has information present in its thickness and the visual variability provided by the passive control.

This information may help occupants to create connections between their energy use in buildings, and the relationship of passive and active heating systems.

3. Objectives

3.1 Research Gap

There is still a distinct gap in knowledge and application when it comes to harnessing solar energy resources - especially over time. Over a year, about 885 million Terrawatt-Hours (TWh) of solar energy reaches the earth's surface - 4,200 times what humanity is expected to consume in 2035. Locally the scope of the problem shifts, as solar radiation varies in quantity and quality by location but also in time, and in ways that are not entirely predictable [IEA 2011, Ch. 2]. Yet - with the exception of solar tracking systems for active photovoltaic collectors - little effort is put into maximizing the solar resource over time, passively or actively (see the review of OI literature in 2.2 above). Instead, passive heating/cooling designs are based on an optimal yearly or seasonal value (i.e. roof overhang distances or optimal angles for photovoltaic conversion).

Informal discussion on this topic abounds and is possibly due to a number of complex and related factors in the traditional design-construction processes; including financial constraints, and the notoriously slow uptake of new technology in the construction industry (see the review of development literature in section 2.5 above). In the case of thermal energy control research, OI mobility is often limited to a static, or simple daily cycle controlled by occupants manually. Perhaps we can do better in terms of response to the constantly shifting energy balance.

3.2 Research Objective

The goal of this project is to develop a solution to the aforementioned problems based on a strong theoretical understanding of the physical energy balance associated with windows, and various additional treatments, and controls as outlined in the relevant literature. Radiative exchanges are dynamic problems and require quick response in order to remain optimized under environmental conditions that can change rapidly. A passive control mechanism that addresses this understanding has been theorized and designed with the aid of rapid prototyping technology. A major research question also exists; will a system with passive control be able to show enough improvement such that deviation from the present norm of night-control is warranted?

This question can be answered with an evaluation of the energy balance of the system over time. This approach can then be translated to windows of other orientations (keep in mind this research is formed with a focus on a western building orientation). Cumulative seasonal or yearly values can then be an effective decision making tool for building owners considering investment in controlled OI systems.

4. Methodology and Research Approach

4.1 Experimentation

In relation to the defined problem, the in-situ experimental approach was chosen for two reasons;

a) to validate the OI effectiveness in the local GTA climate

b) to collect primary data to form the basis for the mathematical model so that results can be translated to a seasonal/annual context and other geographic locations (see chapter 5).

The experiment was developed to better understand the thermal interaction between room, windows, window treatments, and the outdoor environment. Design, construction, and installation of a representative static prototype aided in discovering construction flaws, and tolerances which may affect proper installation (i.e. air sealing), and operation of the passive control.

The secondary data collected from the University of Toronto weather station is used to

a) validate the experimental temperature data

b) apply solar irradiance data to the radiation terms of the mathematical model

c) derive an average wind-speed for use in the exterior convection expression

4.2 Design

4.2.1 Unit Design

A customised operable insulation (OI) system was created for the experimental testing (see Figure 4.1 on the next page). It consists of two 2 inch deep frames and inserts composed of rigid extruded polystyrene (XPS) insulation. Rigid insulation is selected for use, as it has the greatest potential for heat savings based on its substantial thermal resistance properties, as well as ease in creating an effective air-seal with windows. Creation of a sealed cavity between insulation material and window is important, since if air is allowed to move freely, it can essentially nullify any thermal resistance benefit; the CCHRC's best performing case studies were those which had the greatest ability to form tight air seals with windows [Garber-Slaght, 2011]. XPS was also used often throughout the literature due to commercial availability and low initial cost.

Dimensions are slightly smaller than the window frame in order to accommodate an Ethylene Propylene Diene Monomer (EPDM) rubber air-seal which deforms from 8mm to 4mm when fully compressed. This seal is adhered along points of contact between the insulation and the window opening (WO) as well as between the frames themselves. Vinyl fabric is also used in some locations to deal with the unknown degree to which the XPS insulation may degrade due to solar ultraviolet (UV) exposure.

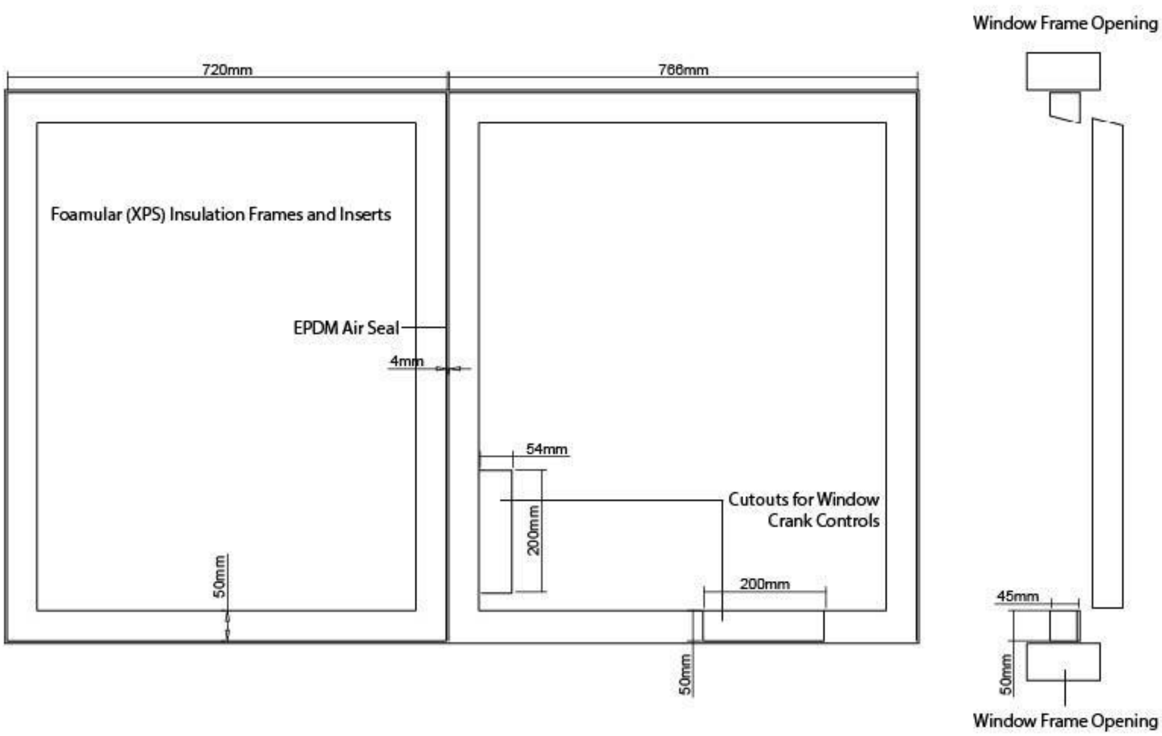

Figure 4.1 Design of the Experimental Static OI – Elevation and Section

The compression fit between frame and inserts, while successful in forming a tight air seal, provided unexpected resistance in adding or removing the insulation panel from its frame. This friction force needs to be reduced in order for the passive control of the system to be effective and is considered in the theoretical design.

4.2.2 The Passive Control Mechanism:

Over the course of this and related research, a method of control was developed by Dr. Liao that is driven by temperature differential and expansion of confined liquid. When calibrated within the normal temperature set-point ranges for buildings (approximately 5°C), this mechanism can provide displacements in the order of 10% of the fluid channel length with a realistic diameter of 30mm.

A diagram showing the relevant inputs and result of the system is presented in Figure 4.2 on the following page.

The mechanism theoretically applied to the OI will be slightly over-sized in order to account for movement of the lightweight operable insulation, as well as the fluid expansion required under the force of gravity. Relative to this consideration, sizes of the movable components are limited to smaller increments (~70mm), and connected with an inclined slider/track system to facilitate operation of all movable components simultaneously.   Slats are oriented at a winter-time optimal angle of 22° from horizontal [29] for incident solar gains for the GTA.

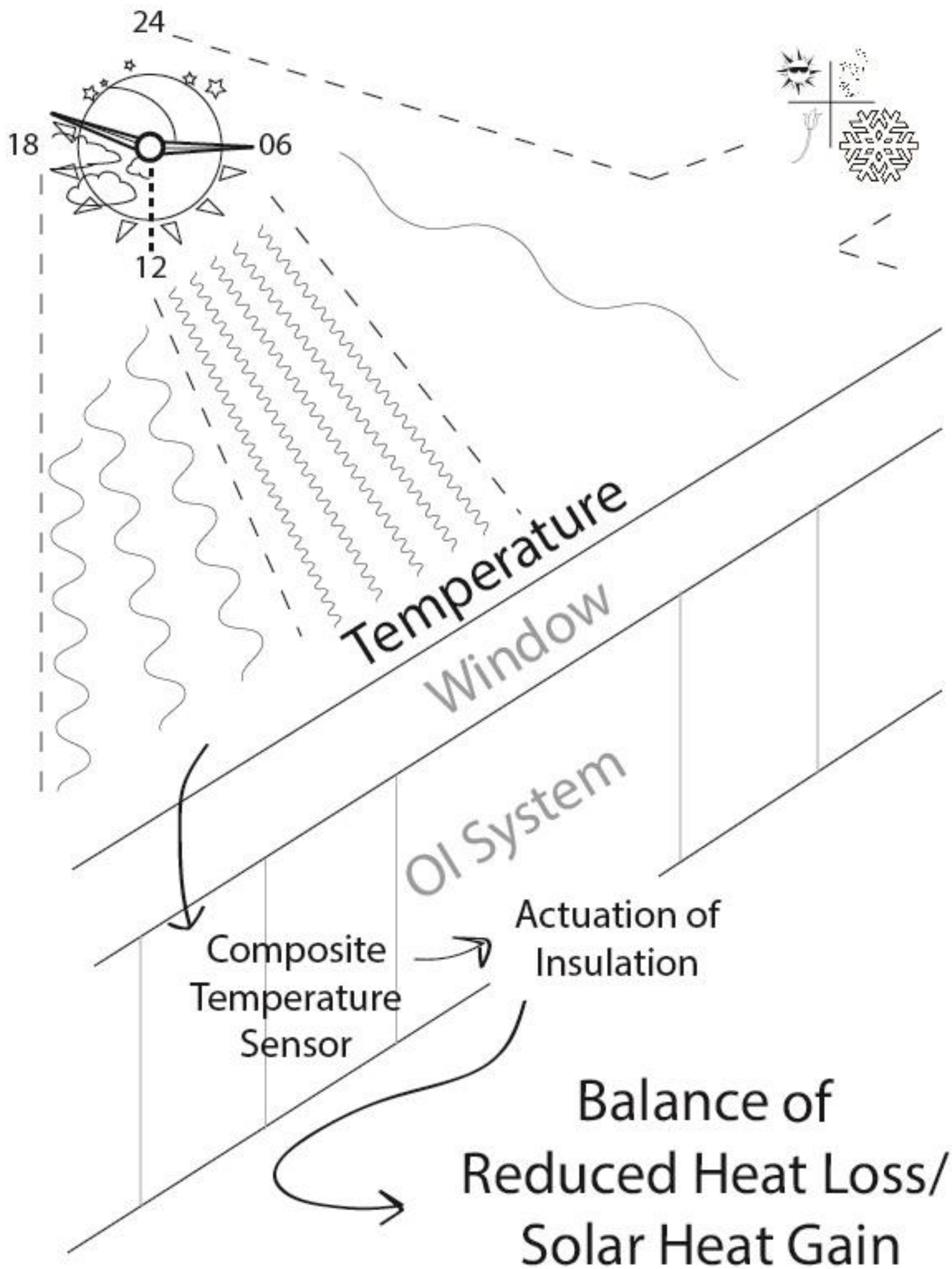

Figure 4.2 Control Diagram

See Figures 4.3 and 4.4 for details consisting of an elevation and section of the design. A light colour, low emissivity material/coating is applied to the top and bottom surfaces of all slats, to enhance the solar heat gain into the room when the OI is open. When open, they may operate as a light-shelf to reflect and admit more radiation. This is done to ensure that radiation/generated heat is transferred into the building and is not able to conduct back through the glass when incident radiation is reduced.

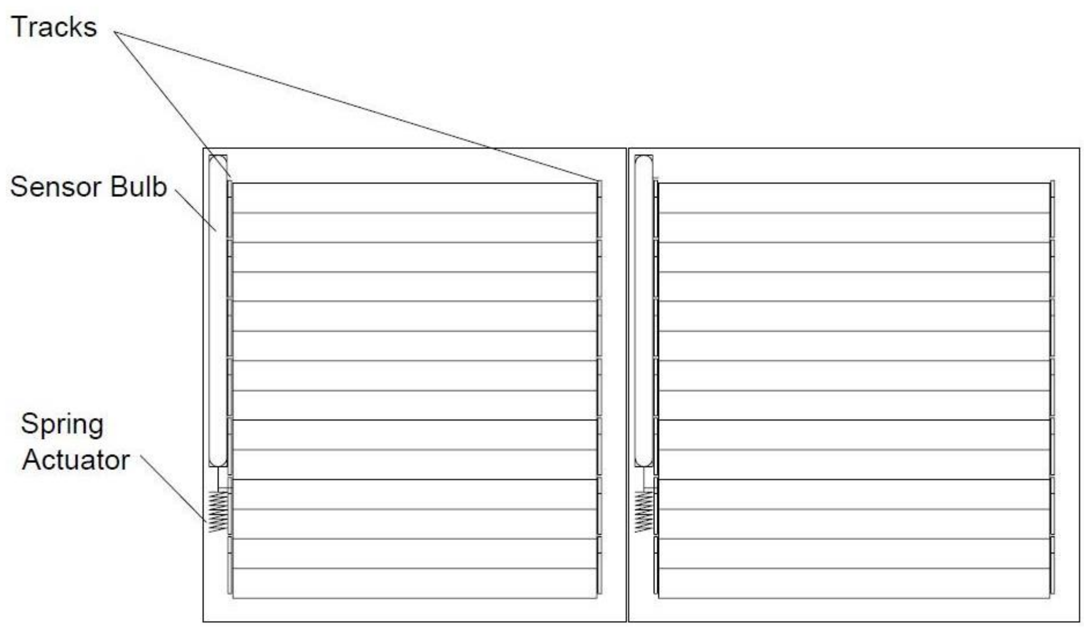

Figure 4.3 Design of the Theoretical Passively-Controlled OI - Elevation

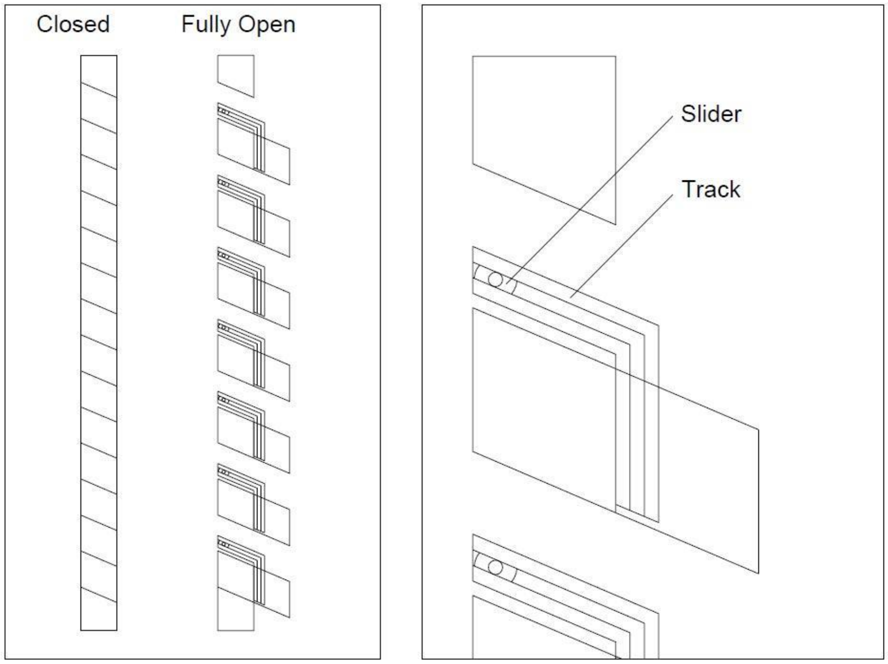

Figure 4.4 Design of the Theoretical Passively-Controlled OI –Section

Translation of the opening components will occur in 2 directions (Y and Z) in order to create horizontal openings that aesthetically mimic conventional shutters or venetian blind slats. A locking mechanism will allow the user to exercise their preferences against the passive control and keep the system open or closed; for views or shading for example.

The XPS product used - Owens Corning's 'Foamular' 250 product has decent fire behaviour characteristics. It has a flame spread rating of 5 (category A) and smoke developed rating of 45-175 - well below the threshold of 450 according to ASTM standard E84. These fire characteristic values have only been evaluated at a surface level and one should note that the specifications recommend the product still not be exposed to an open flame/ignition source. Take note of the fact that it also has a thermal resistance improvement associated with aging from RSI 1.76 to 1.87W/m^2K [Owens Corning 2013.

The sensor bulb is sized at a length of approximately 525mm (501+24mm for a 10%

estimated force adjustment) with a 30mm diameter. This allows for housing within the OI's 2 inch frame. A small hole located at the halfway point of the frame's height will be used to admit the cavity air for contact with the sensor bulb.

The OI system's passive control is designed to operate for the heating season only. The sensor bulb will be calibrated to react between a range of 22°C to 26°C - the typical spectrum of home heating system set points. This ensures that heat loss through conduction is resisted until opening.

When the cavity temperature is appropriately hot (greater than 26°C), the OI components will be fully open to admit solar radiation. When the cavity temperature is appropriately cold (lower than 22°C) the OI moving component will be fully closed, providing the additional thermal resistance value.

A locking over-ride mechanism is included for use in the opposing cooling season, or for if an occupant chooses to exercise their preference for an open or closed condition.

4.2.3 Unit Design Limitations and Assumptions

- The effect of thermal lag is assumed to have little impact on system efficiency.
- Condensation potential has been assumed negligible due to the good degree of daily/weekly variability in the system's open/closed states, allowing for timely evaporation to avoid development of moisture issues in the window sill or frame. In addition, the XPS and EPDM are resistant to moisture migration due to low permeability values, thereby limiting introduction of new moisture into the cavity during closed periods.
- Window damage due to excessive heat build-up has been noted in some of the literature [18]. It is unknown to what degree the function of summertime solar shading (i.e. hot cavity conditions under closed-override) would contribute to this phenomenon under the climatic and design differences of this study.

4.3 Setup and Equipment

Wong's [2008] research provided insight into the modern window construction(s), and the primary characteristics contributing to heat loss. Thermo-graphic imaging with the use of an infrared camera according to her research was the first experimental method devised due to the simple visualization associated with the technology (see Figure 4.5).

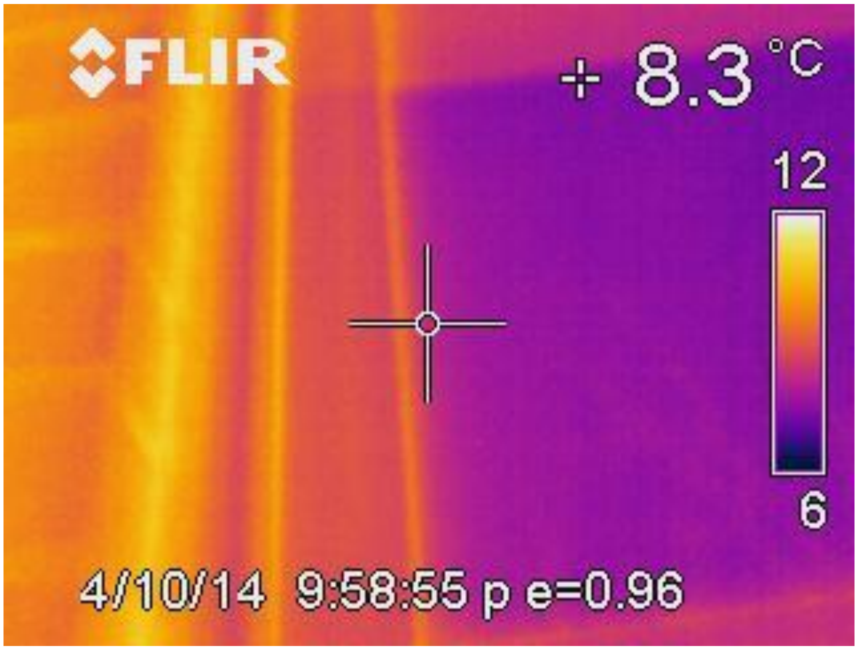

Figure 4.5 Infrared Image of the Exterior of the Window Assembly/Wall

This provided the basis for instantaneous data collection at a surface level. While allowing for comparison to the COMSOL surface colour plots, these images provide little performance information with regard to the interior window assembly layers. It is for this reason that thermocouple measurement became the primary method of data collection. Infrared imaging offered one additional aide in the form of the infrared camera's user's manual, which provided good insight into proper testing procedures with the use of thermocouples [FLIR Systems 2006, 111].

Liu's [2012, 432-443] experimental validation of performance of night-time insulation utilizes a series of thermocouples with a data logger. This method was chosen for the simplicity of collecting data over long periods and working as a basis long enough to provide accurate data for a seasonal context of this study. In addition, it allowed for a stratified profile of surface temperatures through the window/OI assembly, which provided a greater depth of analysis.

Two identical windows (about 6 feet apart) located in the same bedroom on the west-facing wall of a Markham home are used. This ensures that there are relatively consistent interior and exterior temperature conditions for comparison. One further south remains bare and one will receive the additional OI (see Figure 4.6).

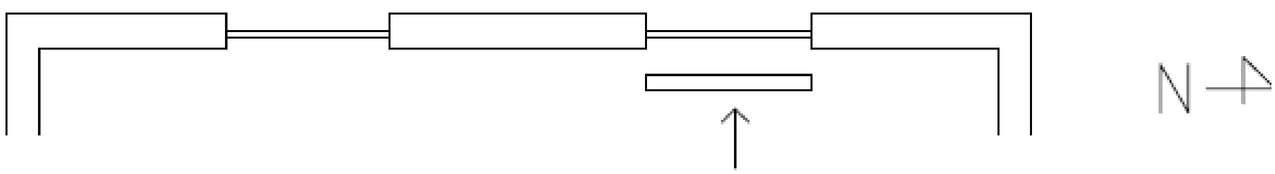

Figure 4.6 Layout of the Room and Windows

Experimental Equipment consists of:

The test environment and windows within a volunteer's Markham home

- Infrared Sensor Camera
- Step ladder
- Thermocouples and Data logger
- Duct Tape
- The OI unit

4.4 Experimental Procedure

Temperature data from the windows was gathered as average values measured over 10 minute intervals, with the use of Fluke - Hydra Series data loggers and thermocouples. A total of 20 thermocouples for each window case are adhered to surfaces of interest using tape, in a manner outlined in the image (see Figure 4.7). This data is used to validate the obtained experimental values as well as the overall behaviour of the mathematical model against programmed environmental influences over time.

Figure 4.7 Photo of Thermocouple Attachments

Thermocouples are arranged in a final configuration in the schematic diagram (see Figure 4.8 on the next page). The thermocouple data used for analysis is numbered in the same Figure.

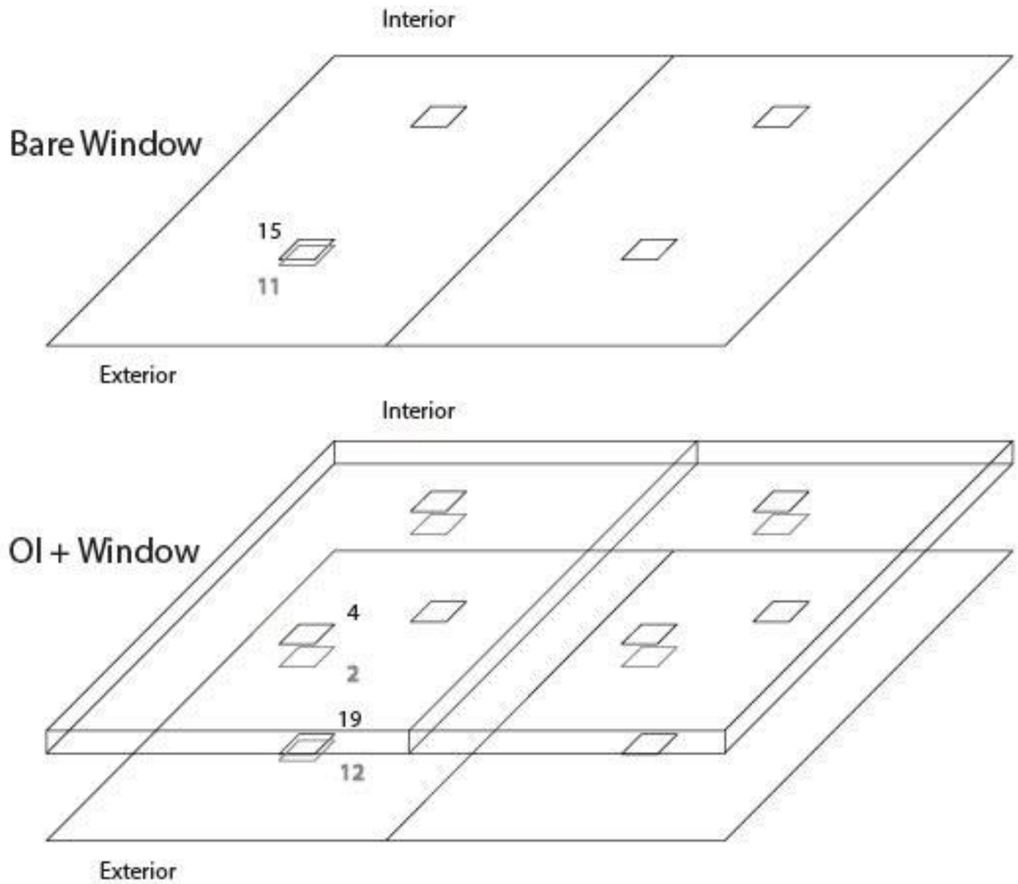

Figure 4.8 Final Thermocouple Layout

1) Air temperature, wind speed and solar irradiance values were gathered from the University of Toronto's weather station over 15 minute intervals. The station's pyranometer uses a horizontal orientation with a 180° field of view to the sky.

2) A temperature data logger collects temperature data for both windows from April 10th-28th.

3) An infrared camera collects thermal image data for both windows from the exterior on April 28th at approximately 22:00.

The results of this experiment will support the design criteria proven by the COMSOL simulation model; an OI object applied to a conventional bare window, will improve upon heat loss (heat flux values) without interfering with the window's normal functionality.

4.4.1 Limitations/Assumptions

- The difference in solar irradiance between the campus and the test home in Markham (~40 km away) is treated as negligible.
- The coloured tape used to adhere the thermocouples to the surfaces is assumed to have an impact on gathered temperature values due to the tape's low emissivity/absorptivity (accounted for in the final COMSOL models)
- Weather station data was corrupted after April 25th and is discarded

5. Mathematical Modeling

The mathematical model built with simulation software is chosen for a few reasons:

a) to provide repeatable simulations using a number of cases and conditions based on our observations from the experiment,

b) to discover and account for parameters that went unmeasured, such as convection and radiation, thereby providing greater understanding of the problem, and

c) to develop animations, graphs and other post-processing aids to assist with visualizations of the problem.

Three major steps formed the final models:

1) Simply construct the problem by mimicking observations as accurately as possible

2) Use COMSOL's global, domain, and boundary specific inputs to derive a model that remains accurate beyond the experimental time period. This included calibrating the model to match the real-world thermocouple measurements (i.e. the effect of the tape)

3) With accuracy established, the passive control is incorporated, allowing for analysis and discussion.

COMSOL Multiphysics software is a finite element modeling (FEM) software which is able to consider numerous physical interactions in both static and transient problems. For the purpose of this research, the conjugate heat transfer (solids and fluids) with radiation, and deformed geometry modules will be used.

Other CFD software used in the literature, such as ANSYS or FEMFAN was either commercially unavailable, unable to model a significant depth of 3D geometric detail for buildings, or required extensive coding knowledge. COMSOL also has a robust post-processing and plotting interface allowing for useful representation of results.

Simulations were performed using a PC with the following specifications:

Primary Workstation

Processor: 2x Intel Xeon (R) E5-2670 @ 2.6GHz

RAM: 64GB

OS: Windows 7, 64 bit

COMSOL version: 4.4

Final model simulation length times averaged around 20 hours using the primary workstation.

5.1 Geometry Materials and Other Global Settings

The model geometry consists of 2 meter wide sections of the wall construction surrounding the windows, spanning the height of the first and second floors. To alleviate the large computational requirements for such a complex model, geometric symmetry was incorporated to reduce model size by one half. The deck and first floor were included due to anticipated ground albedo (reflection) and/or convection effects. The individual components of the wall and frame constructions were not modeled, as only the exterior surface is of relevance for radiation effects. Composite values are used instead. The wall's thermal conductivity, density and heat capacity are specified as average values for a Canadian , brick clad, 2x6" construction built to meet an R21 requirement as per local building code (see Table 5.1 below).

Input of relevant material properties of the construction components are based on data incorporated into the COMSOL material databases where possible and from other data sources [ASHRAE 2009, Ch. 26][Engineering Toolbox, 2014].

Material	Model Use	Thermal Conductivity (k) $W/m \bullet K$	Density (ρ) kg/m^3	Specific Heat Capacity (Cp) $J/K \bullet kg$	Surface Emissivity - long wave	Surface Emissivity - short wave
Air (still)	Air	0.024	1.2	1005	-	-
Composite Brick Wall	*Wall*	0.04	400	1750	0.85	0.85
Foamular	*OI*	0.023	32	1400	0.6	0.6
Wood	*Deck*	0.12	450	2500	0.82	0.82
Composite PVC Frame	*Window Frame (*Composite)*	0.5	230	2000	0.75	0.75
Glass	*Window*	1	2500	840	0.95	0.1
Polyethylene (dark)	*Tape*	0.33	910	2000	0.8	0.8

Table 5.1 Model Material Property Inputs

Tested configurations consist of:

i) the bare window 1) the OI window - static 2) the OI window - night control and 3) the OI window with full passive control

Meteorological (solar and outdoor air temperature) functions are derived from data gathered in the experimental phase. A correction accounting for the effect of Sol-Air surface-film heating has been added according to values estimated based upon a nearby geographic location at 45° latitude for July 21st.

Tham, & Muneer [2011, 1243-1250] define sol-air temperature as “the outside air temperature which, in the absence of solar radiation, would give the same temperature distribution and rate of heat transfer through wall or roof as exists due to the combined effects of the actual outdoor temperature distribution plus the incident solar radiation.” Since the insulation is the first opaque geometric element encountered through the window assembly, the Sol-Air correction is applied at this surface. Other definitions of Sol-Air temperature like that of Tham & Muneer [2011, 1243-1250] include all atmospheric effects but since it is not an intrinsic climatic effect [O’ Callaghan 1977, 307-311]] but instead a quantity for simplified load calculations, we will consider exterior convection separately.

Unfortunately, sol-air temperature data is difficult to locate, particularly for the heating season. This makes sense as it is a quantity often used in determination of cooling load. The corrections have been interpolated from a combination of the July 21st data as well as that for December 21st at the same latitude location [Hutcheon 1983, table 9.7].

5.2 Heat Transfer Module

Conduction

The heat transfer module is used to model the heat transfer for all physical domains (both solid and fluid). Refer to Equation 1 in Appendix A.

An interior temperature boundary was used to simulate interior conditions with a simple set point of 22°C. The exterior temperature function was applied to all exterior facing surfaces.

Convection

Convection effects are considered negligible with the exception of the building exterior, where convective heat flux is used to account for the heat loss due to wind movement along the building.

A forced convection was specified based on an average wind velocity and the size of the window. COMSOL utilizes convection terms derived from ASHRAE plate heating convection principles in table 5 [ASHRAE, Ch. 4]. Refer to equation 2 of Appendix A.

Radiation

An external radiation source using solar position, irradiance, and geographic data accounts for the incoming solar radiation from the sun (refer to equation 3 of Appendix A). Radiation direction was specified as unidirectional from the solar source position, with the model positioned at its true geographic location on earth.

Latitude: 43.86°

Longitude: -79.35°

Time Zone: Eastern (UTC + 5)

Figure 5.1 on the next page is an example of a surface temperature plot with radiation effects.

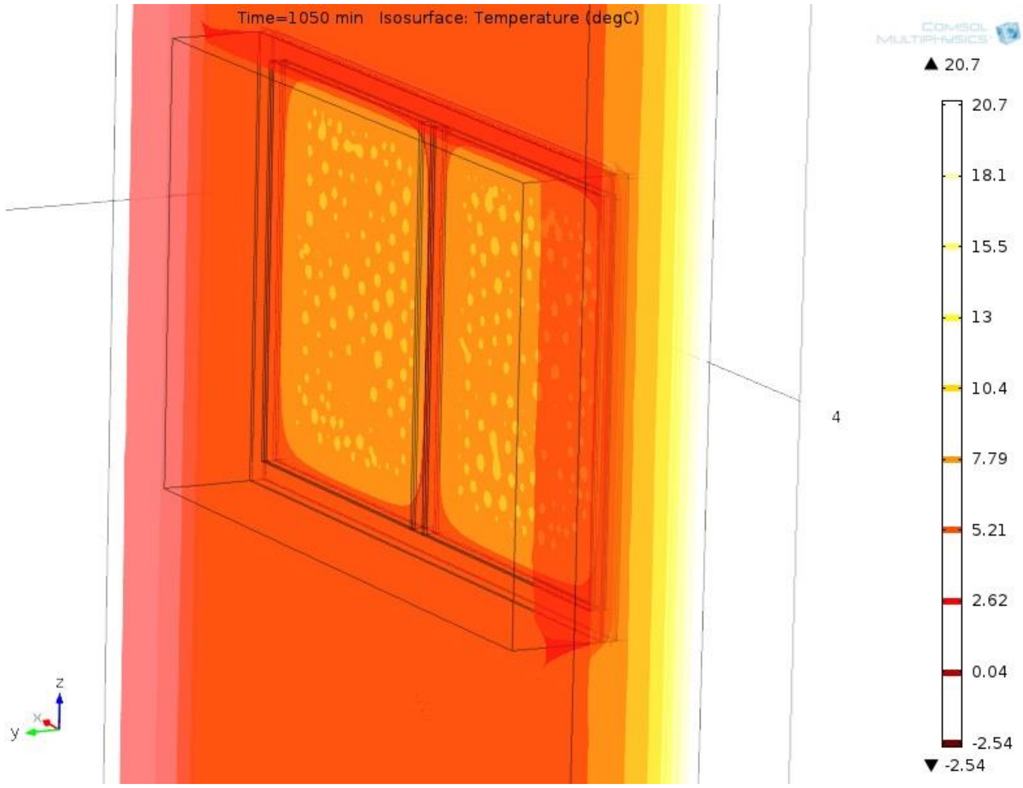

Figure 5.1 Surface Temperature Plot

Spectral dependence of emissivity is split at a threshold of 2500 micro meters into the solar (short-wave) and ambient (long-wave) bands to accommodate the physical behaviour of a modern glazing assembly [EWC, 2011].

The use of single surface to surface and ambient radiation boundary conditions throughout the literature is appropriate for mutual irradiation of surfaces and is continued in this research. Please refer to equations 4 through 10 in Appendix A.

5.3 Deformed Geometry Module

The geometric domain of the OI moves according to a prescribed displacement of the spatial frame, set to trigger when air temperature of the insulation cavity exceeds 26°C. This is done through a component coupling that reads the average temperature values at the exterior face of the insulation (see Figure 5.2).

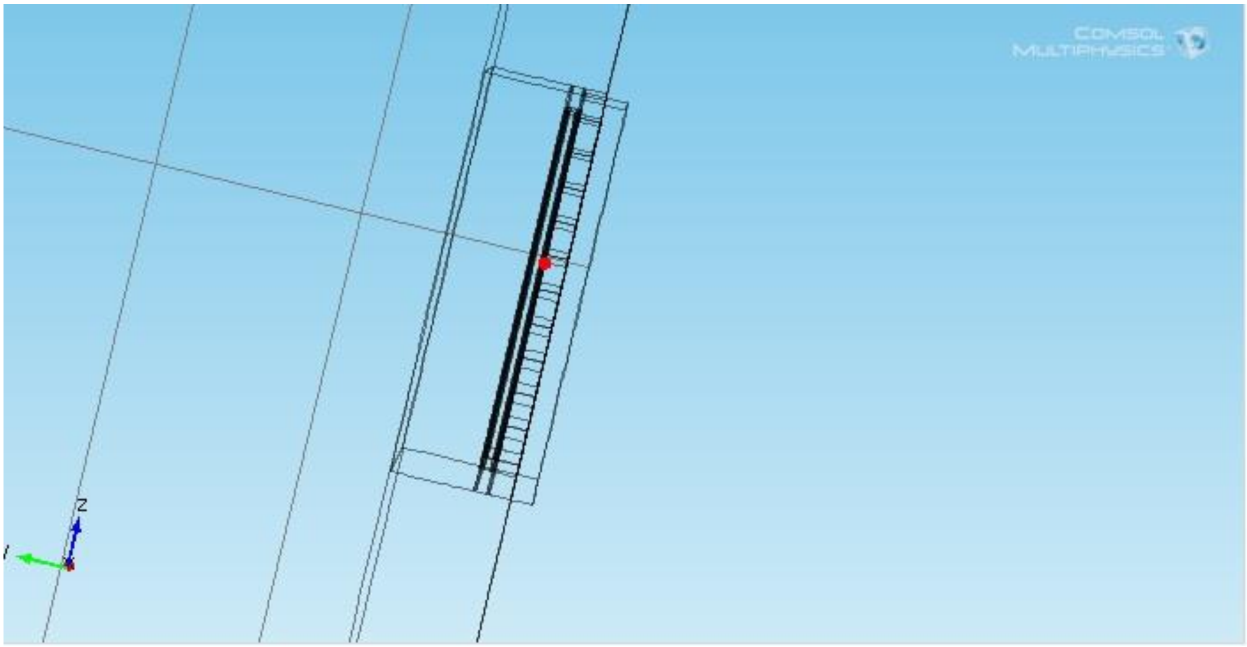

Figure 5.2 Component Coupling Locations

This is then called upon by the expression for prescribed displacement (movable insulation domains selected), which is active in the z and y directions, allowing for opening/closure of the OI. Prescribed domains (i.e. moving slats) are seen in Figure 5.3.

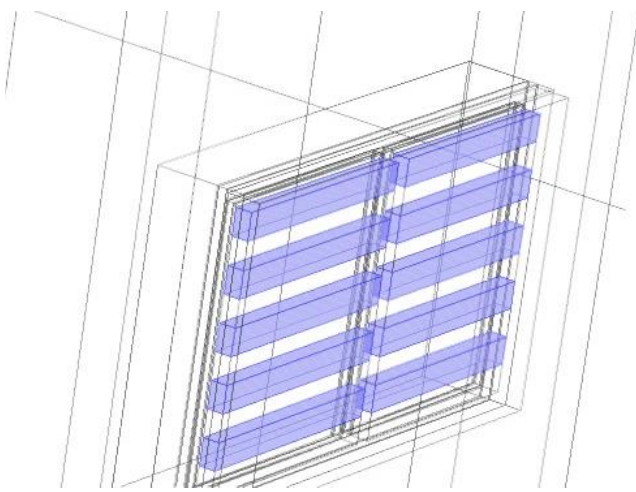

Figure 5.3 Moving Slat Selection

For the night-control system, opening and closing occurs at 7am and 8pm, respectively. To maintain consistency, heat flux measurements will be taken from the location of the interior surface of the insulation; the 'window-room plane'. This fixes the thermal flux value to the area of the window itself, and ignores other factors which can vary greatly among homes, such as home size, heating system efficiency etc. Examples of the heat transfer physics (seen from the interior) interacting with the deformed geometry according to the described control are seen in Figures 5.4 and 5.5 on the next page.

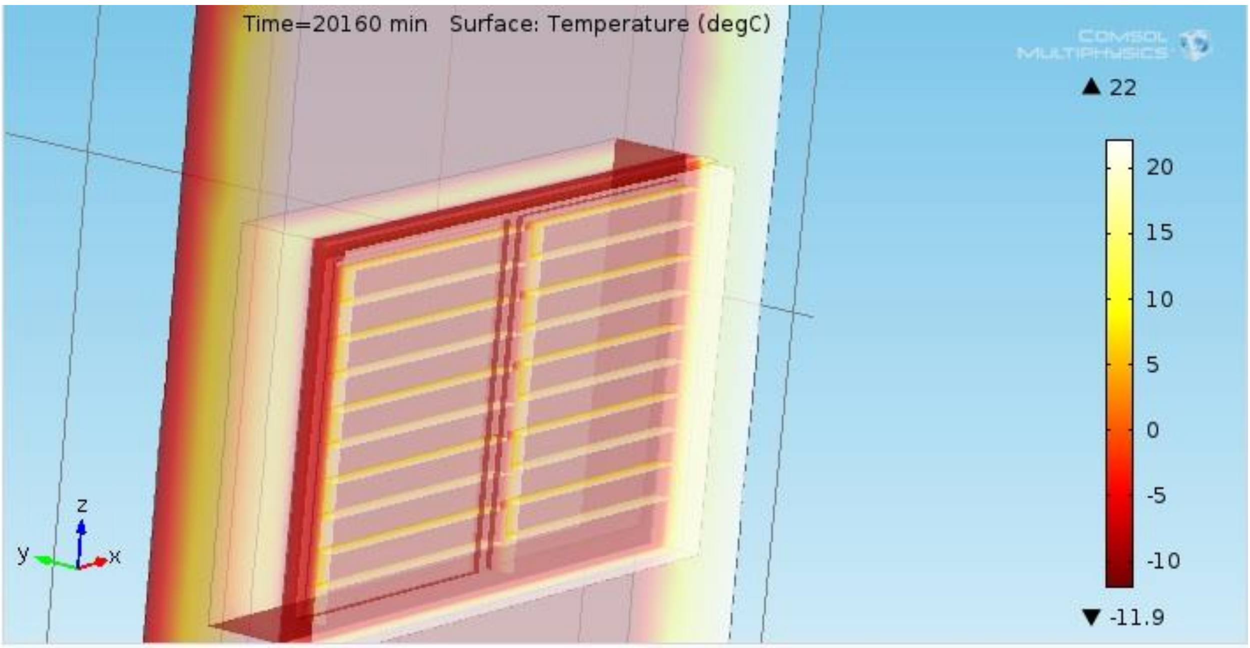

Figure 5.4 Closed System Temperature Plot

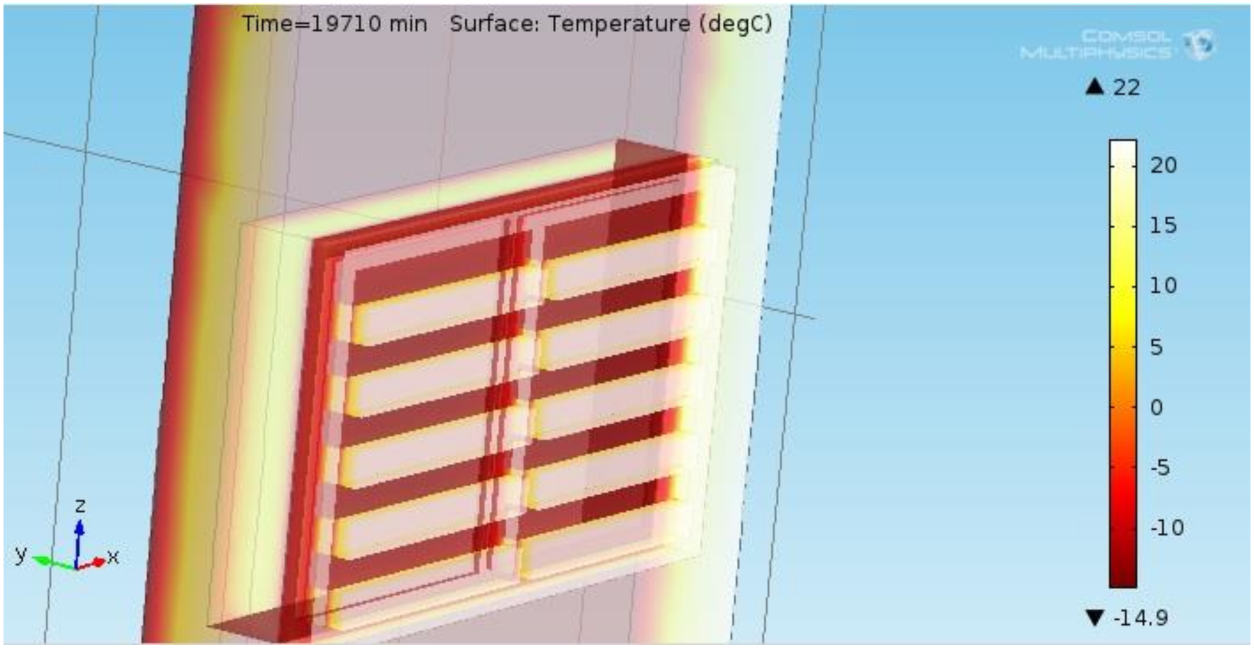

Figure 5.5 Closed System Temperature Plot

5.4 Meshing

The mesh acts as a framework in which the physics are calculated throughout the space dimension using the finite-element method. As the mesh size decreases towards zero, the results move closer to an exact solution. However, limited computer resources can only handle so fine a mesh. Tetrahedral was used as the shape order, as it is the most efficient for most physics, and also is more stable for use in adaptive mesh situations such as deforming geometries. [Frei Nov. 2013]

Early in the modelling process (and while using different software versions) – user controlled meshes were required due to to large differences in domain sizes that were not automatically resolved – for example between the wall and smaller window frame components. Element size varied from “normal” to “finer”. Normal and fine sizes produced warnings that “Edge is much shorter than the specified minimum element size”.

When model size is reduced by half due to use of symmetry, thus reducing computational demands, use of the automatic physics-controlled mesh (seen in Figure 5.6 below) is sufficient.

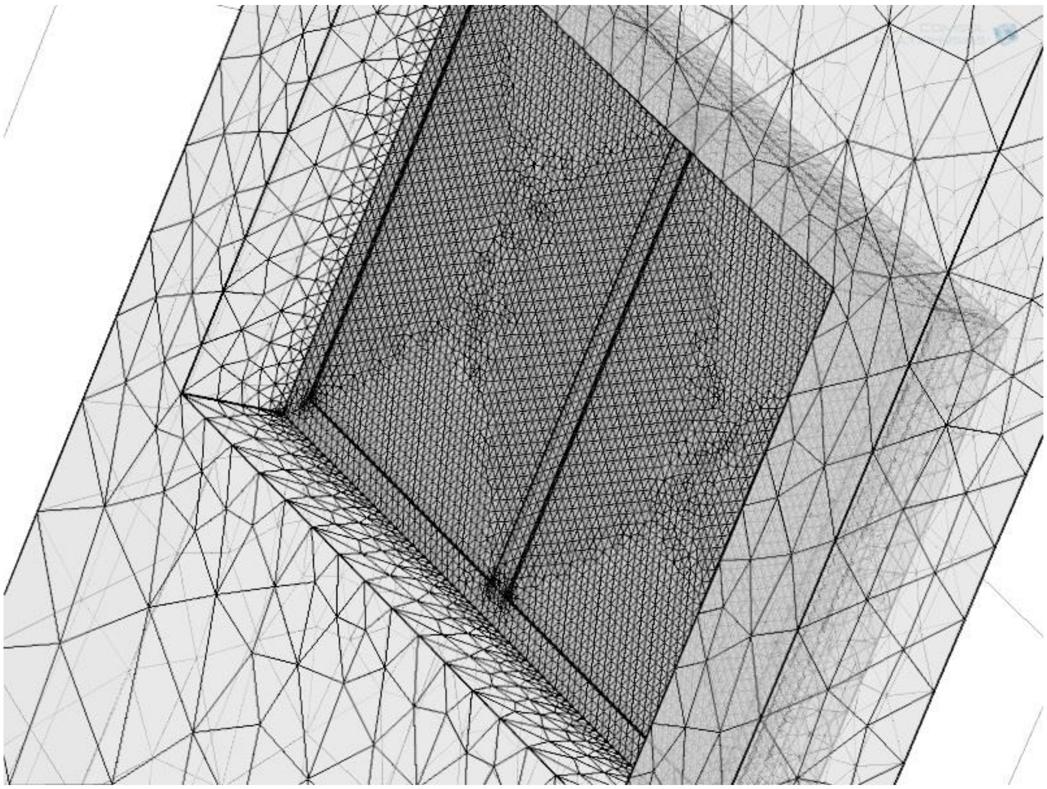

Figure 5.6 Physics-Controlled Meshing

Element size is specified as “finer” throughout to provide good resolution of results. Physics-controlled meshing incorporates features such as corner refinement and determines optimal element size and distribution throughout the geometry.

5.5 Limitations/Assumptions

- The convection loss effect from wind across the building exterior is based on a year-average velocity value of 4 m/s.
- Glazing is treated as opaque on the ambient spectral band
- The hemicube method (180° field of view similar to U of T pyranometer setup) for radiosity propagation is used, and therefore angle of incidence reductions in transmission is assumed and accounted for
- The method of adapting radiated surfaces to the deformed geometry was unknown and therefore not performed, but should be included in future research as it is assumed this would provide a more accurate model and contribute to a greater amount of overall incident radiation and therefore heat gain. The moving mesh module may be more suited for this. See Figure 5.7 below, where a radiosity plot shows that radiation does not fall on the newly created horizontal surface.

Figure 5.7 Radiated Surface Limitation

- The modeled window does not include spacers and other visually inaccessible window-frame technology meant to limit thermal losses

6. Results and Analysis

To reiterate, the research goals of this project are as follows:

- to determine the effectiveness of OI under the climatic conditions of the GTA and
- to assess the feasibility of a fully passive control relative to a night control for an OI system based on the energy savings.

6.1 Discussion

The meteorological data (Figures 6.1 and 6.2) shows that there is a large degree of variability of GTA climatic factors and underscores the hypothesis to the problem, by focusing on dynamic response. The daily extremes or swing of exterior air temperature can vary at about 15°C on average, but longer periods (a few days) can see swings of close to 35°C.

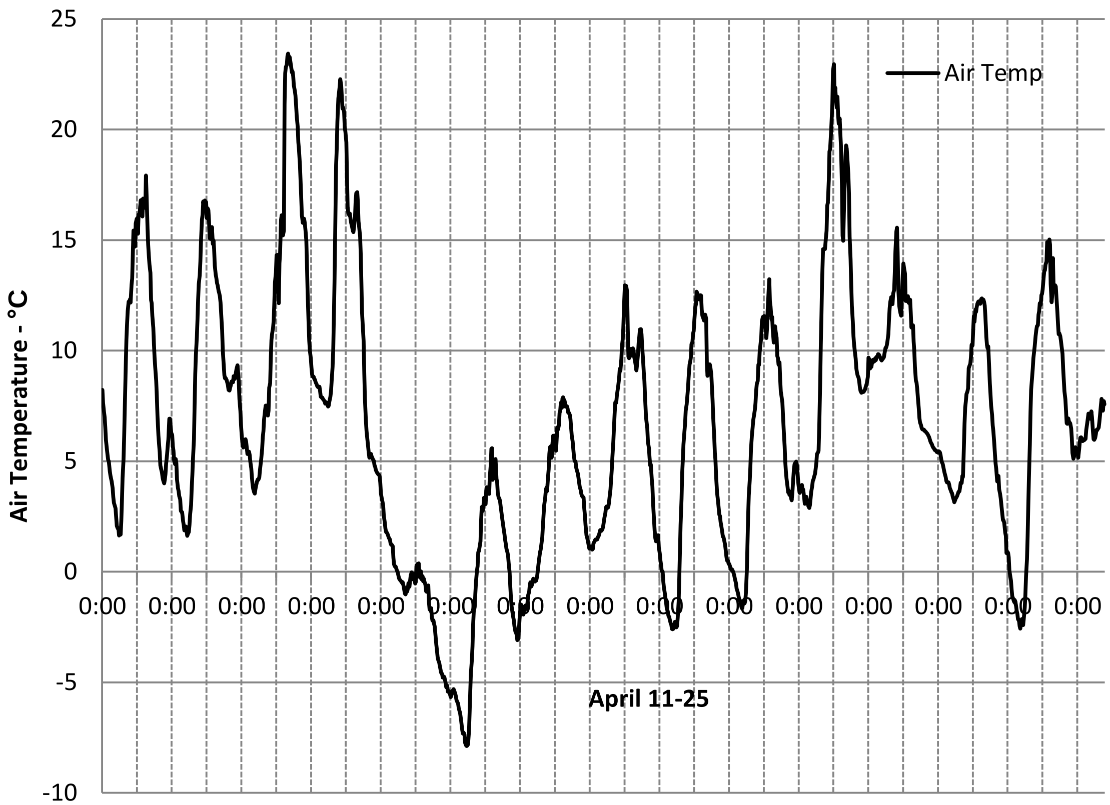

Figure 6.1 Air Temperature, April 11-25th

Figures 6.2 shows the dynamic nature of the problem in terms of solar gain. Irradiance values can change rapidly. There are differences of as much as hundreds of W/m^2 over intervals as short as 15 minutes. This is due to various local conditions

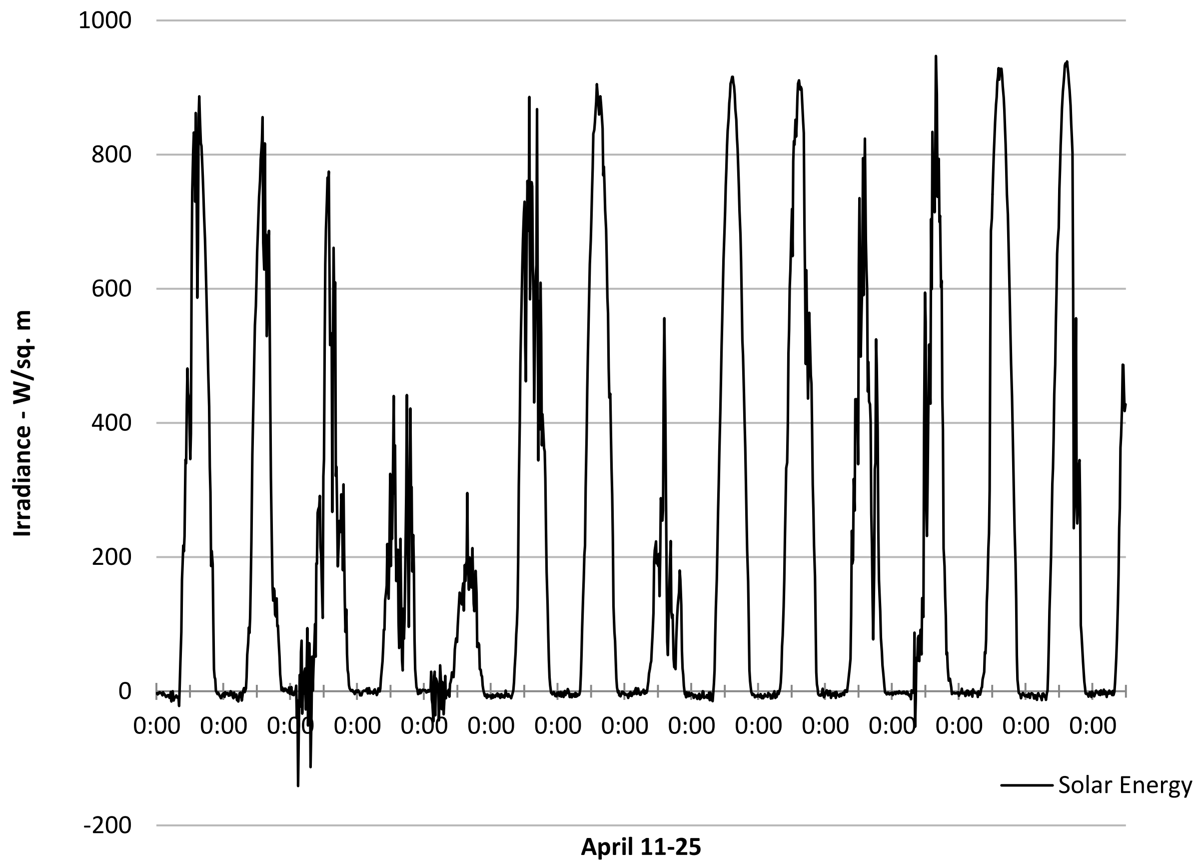

Figure 6.2 Solar Irradiance, April 10-25th

. The testing of the bare window against the static system is also indicative of the dynamic aspect of the problem. The normal window bare window (see Figure 6.3) is less subject to the full daily temperature extremes, while the OI window (see Figure 6.4) experiences greater changes in temperature. This does not represent the entirety of the problem however, as these values are only derived from surface temperature and does not consider radiation effects.

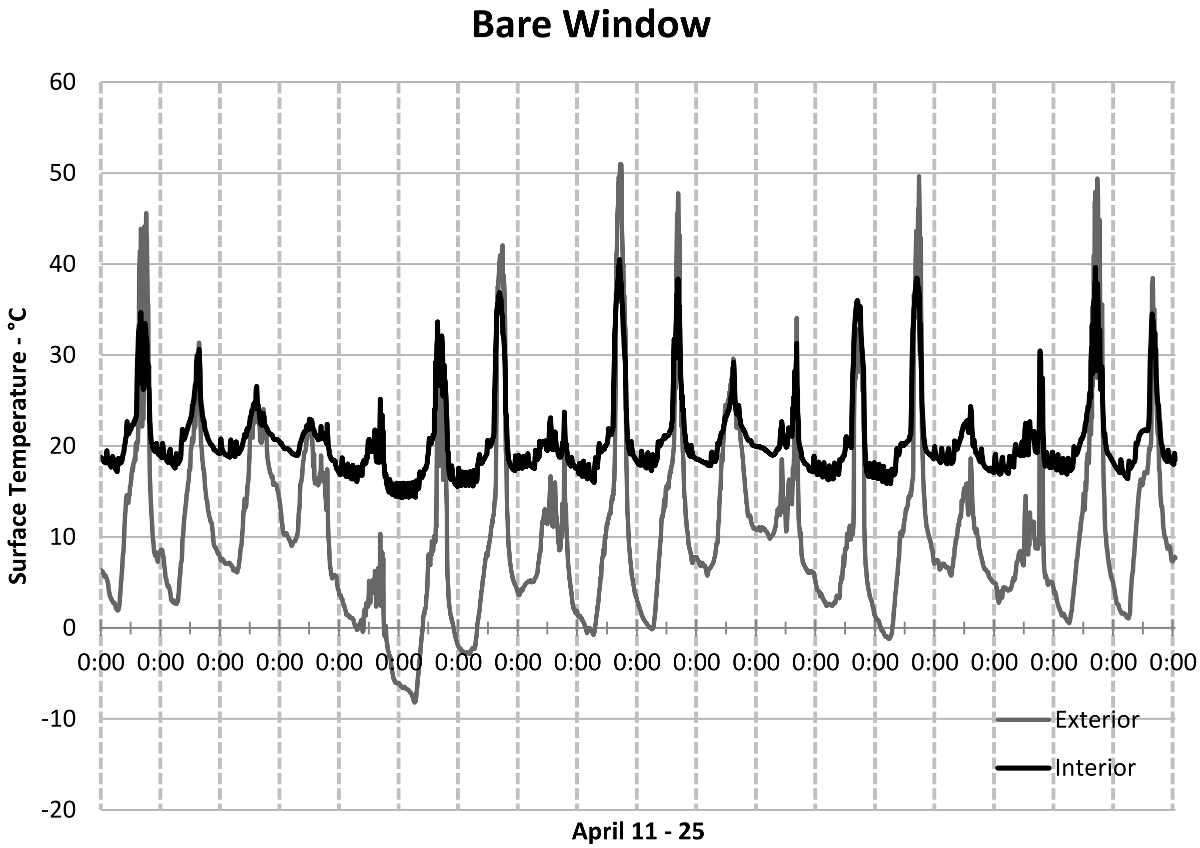

Figure 6.3 Bare Window Surface Temperatures

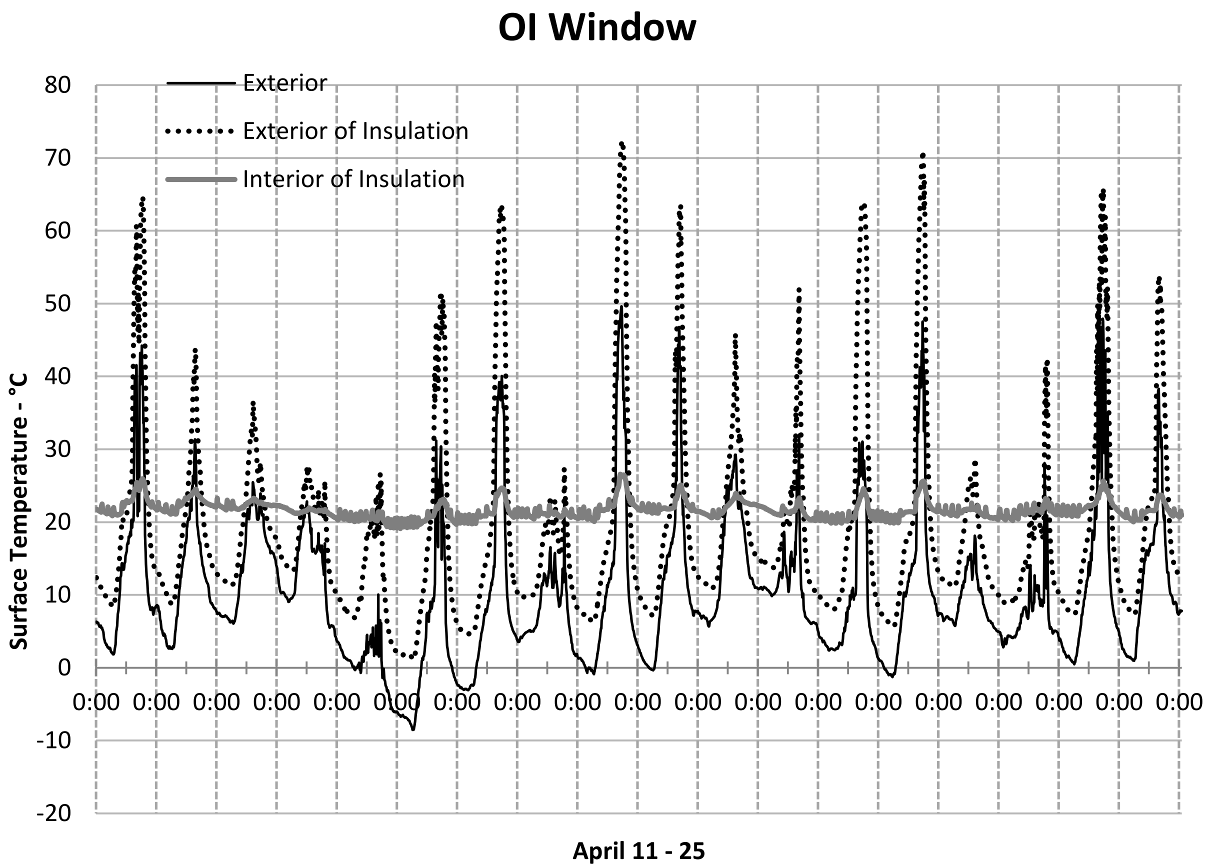

Figure 6.4 OI Static Window Temperatures

Figure 6.5 shows the same measured phenomenon for each window, but as a metric of heat flux (W/m^2) taken at the interior room-window-plane. The area between the dotted and solid lines, shows the difference between an open and static system. It indicates great potential for reduced heat flux during colder and/or low-solar gain conditions. Hence the popularity of the night-time control scheme for OI.

Notice the negative values. They show gains that are exaggerated for an open window condition. This is due to the radiation based heat build-up in the static system, and radiation heat penetration of the bare window, respectively.

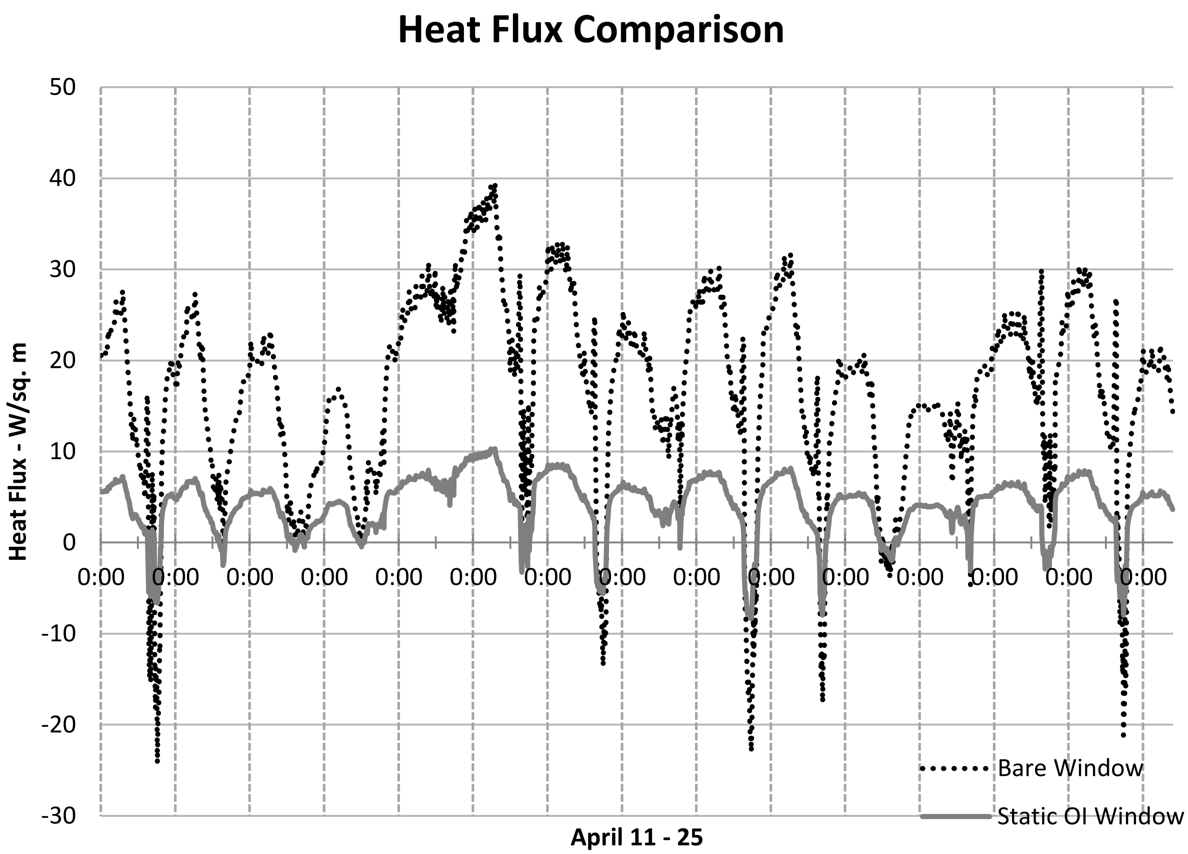

Figure 6.5 Recorded Heat Flux Comparison

Figure 6.6 measures the simulation results (long dashes) against the surface temperatures collected by the thermocouples. Simulation results closely mimic measured values at the same location. Difference, particularly in the length of period of peak heating, is due to the listed modeling limitations/assumptions.

COMSOL results are being taken at the same window locations as the thermocouples, with use of 3D cut points for mapping of values in the window assembly and other geometry.

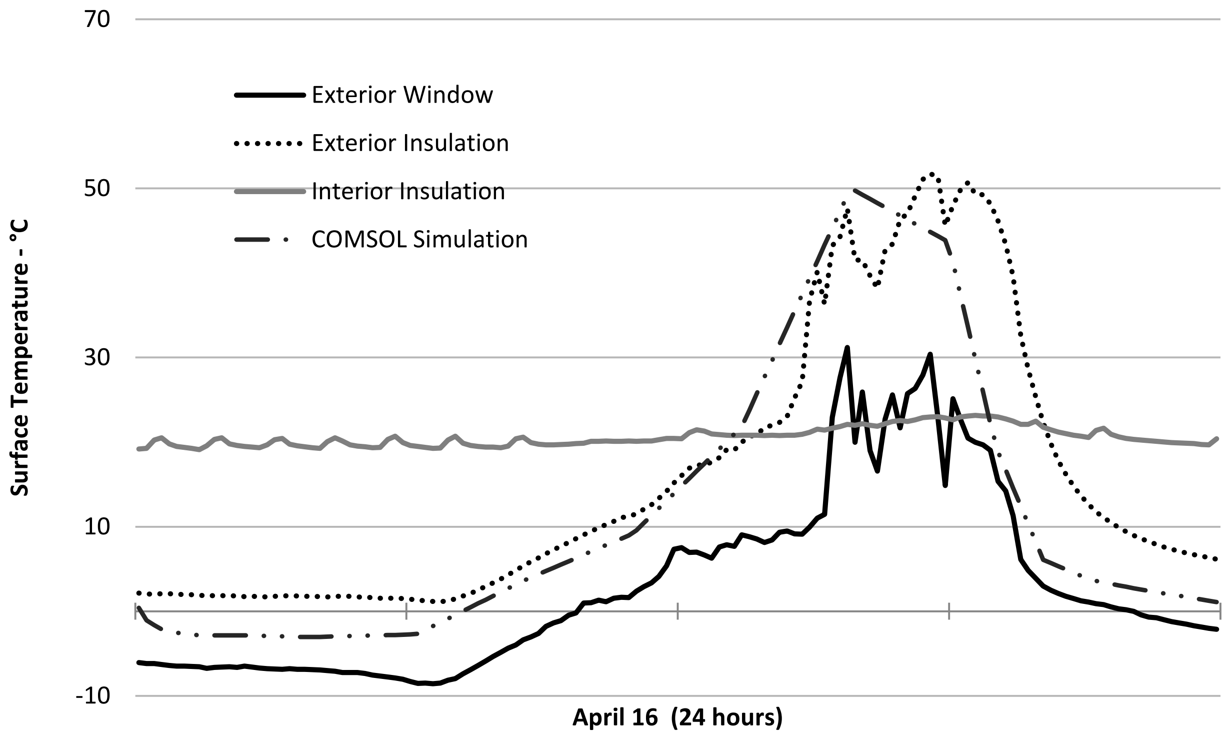

Figure 6.6 COMSOL Simulation Results vs. Recorded Results

The comparison among Figures 6.7 and 6.8 (see below) shows the negligible difference between static and night-control systems in terms of the magnitude of total heat flux for April 16. The static system performs better in limiting losses, while the night-control performs better in terms of heat gains. As heat flux is a vector quantity, positive values indicate heat energy lost from interior to exterior, while negative values indicate heat energy gain from exterior to interior.

The integral of the curve totals approximately 3353 J/m^2 for the static system versus 3420 J/m^2 for the night control. This is a difference of approximately 67 J/m^2 over the day, a negligible improvement by use of a static system of about 2%.

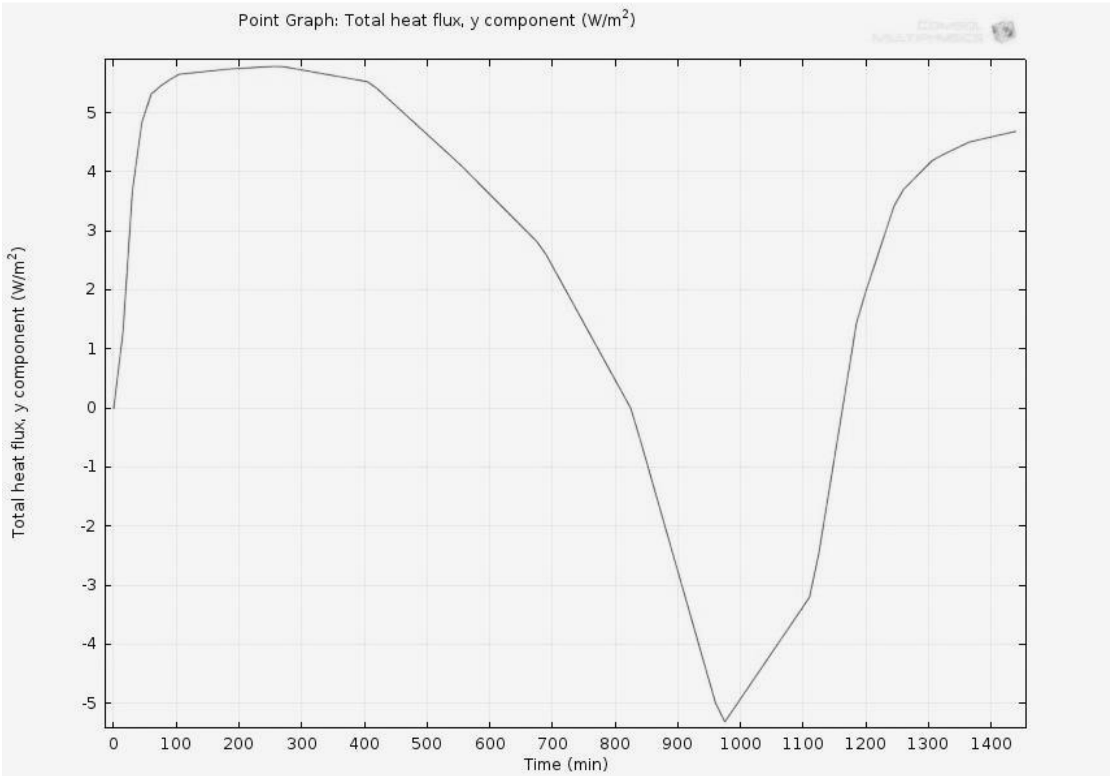

Figure 6.7 COMSOL April 16 Simulation – Static Control

Figure 6.8 COMSOL April 16 Simulation – Night Control

Further comparison to the full control condition (Figure 6.9) shows a greater level of overall responsiveness that does not suffer from the small peaks in heat loss associated with the timely opening of the system or lower gains associated with a static system.

Heat flux totals 2023 J/m^2 for the full control system. This is a difference of approximately 1333 J/m^2 less than the static/night-control systems, or close to a 40% improvement.

Figure 6.9 COMSOL April 16 Simulation – Full Control

Unfortunately, COMSOL cannot produce accurate studies longer than 24 hours on its own. This is due to the fact that the solar positioning entries are restricted to day, hour and minute values. The following is a selection of a heating season day where the full control improves upon heat flux savings provided by either the static or night-control system in the heating season.

The simulations (Figures 6.10 and 6.11) show a greater overall heat flux savings for the full control system, which on this day, December 1, only opens for a short period to optimize the building energy balance. As one can imagine, a static control would perform better than a night-control system and almost as well as the passive system on this day.

The integral of the heat flux curve totals approximately 8393 J/m^2 for a night control system, versus 6058 J/m^2 for the full control system. This is a difference of approximately 2335 J/m^2 over the day, close to a 28% improvement.

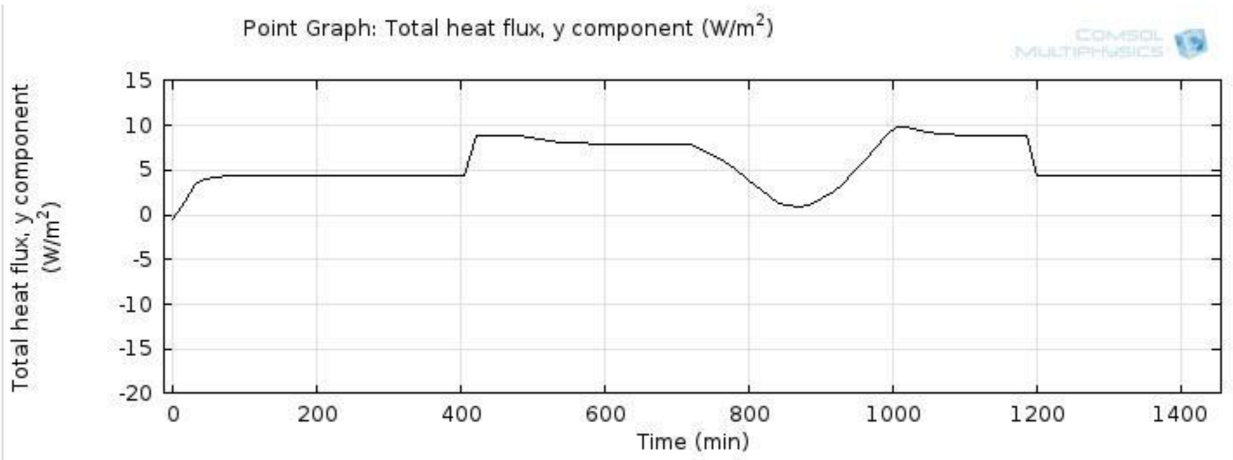

Figure 6.10 COMSOL Dec 1 Simulation – Night Control

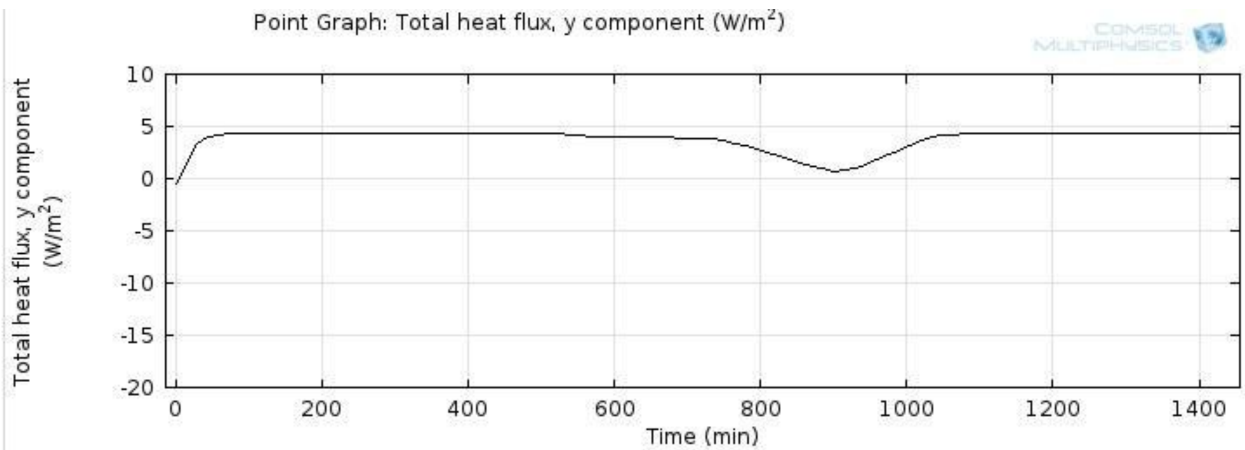

Figure 6.11 COMSOL Dec 1 Simulation – Full Control

6.2 Conclusions

The comparison of static, night-control, and. fully passive controls for OI systems reveals that the controlled system performs better in terms of heat flux savings than a static system, or night-control system as expected by around 28-40%. Surprisingly, a static system can outperform a night-control system, though this is largely dependent on the chosen opening and closing times. This adds to the inherent drawbacks associated with manual user control; how is an occupant to determine optimal operation times for each day?

The shoulder season (April) shows more significant savings in terms of improvement, though the magnitude of savings is higher in the depth of the heating season (December). This is due primarily to meteorological factors including; colder temperatures, and reduced solar gain periods (later sunrise and earlier set). While local shading/masking conditions from cloud cover are no more dynamic than those of the experimental period, the colder temperatures affect the optimization associated with opening. It is an important factor even though opening is limited to periods of greatest solar gain (i.e. to generate cavity temperatures of 26°C).

Longer studies need to be conducted to validate the full heating season and year-round heat flux improvements over static or night-control systems. However benefits are evident based on the daily 1333 J/m^2 savings in April – the spring shoulder season; and the 2335 J/m^2 savings in December – the middle of the heating season. A cursory estimate of the benefit of a full control over night/static control for the full heating season follows:

The heating season length according to a GTA minimum heating by-law is about 250 days at a threshold of 21°C for outdoor air temperature; effective from September 21to June 1 of the next year [City of Toronto]. This value is for a MURB, and detached homes are assumed to have a similar schedule. Assuming that over the season, a fully-controlled OI system provides an average savings between the deep heating season (December) and shoulder season (April) values; produces an average daily savings of 1834 J/m^2 of west OI system. Applying this to the length of the estimated heating season for homes, produces an annual savings of approximately 458,500 $/m^2$.

The tested windows are a size of 1.35 m^2, so heating energy savings over the other simulated static and night-control systems, total 618,975 J per west OI system. This is not an overly large value in the context of building energy use, but is an improvement that provides more optimal operation of the OI system than a static or night control can offer. Therefore, a constantly responsive passive control system is feasible based on the additional energy savings it yields. Not only does it provide responsive control over time that is superior to a nightly or static control scheme, but it also eliminates human error factors that would affect the practical efficiency of a manual, night-control OI system. It essentially provides the best of a static system, with a better response to solar gains than is afforded by simply opening in the morning and closing at night.

In summary, a passively controlled system performs best due to the inefficiencies associated with the timely opening of a night-control system and lower thermal gains associated with a static system.

7. Context

7.1 Global

This study is important because it deals with achieving an optimized building energy balance at an end-user level. The fact that a simple passive control can be implemented (at low cost, as well as complexity of installation) into a window energy transmission system such as those under study by the CCHRC [Garber-Slaght 2011]] or constructed by Liu et al. [2012, 432-443]] or Hansanuwat [2010], is a step beyond the simple daily cycle of manual control and can provide improvements in building energy balance to reduce loads on active heating systems. This passively controlled system will also allow for a more energetically responsive degree of control, thereby improving window-adjacent spatial comfort (thermal conditions) for occupants in all seasons. It will preserve the function of fresh air entry/exhaust should it exist within the current window and allow the user to exercise their preference at any time contrary to the control scheme.

This research is suited to a large global context of northern climates or climates with a defined heating season (i.e. much of North America, Europe and Asia), where building heating systems are a primary consumer of energy. It is also applicable to groups of buildings that suffer from poor solar design or excessive window use throughout the envelope.

7.2 Construction Technology Diffusion

This system allows for modulation of the interior environment in a post-occupancy, retrofit scenario without the use of active systems and therefore makes it an attractive option for buildings with windows that are not optimally oriented for solar gains.

The systems design portion of this research has an additional requirement of producing a design that will have immediately recognizable benefits to help facilitate its use. This has been addressed with regard to occupants through the theoretical design. However, there are two major decision makers that can be targeted in this case; building end users (occupants), and constructors/renovators. Mitropolous and Tatum [2000] outline cognitive processes which apply to both groups of decision makers listed above, and due to the energy saving potential, comfort, visible aesthetic and other architectural implications this research speaks positively to every decision-making perspective in some manner. While this is not a major focus of the research it remains an important consideration in the systems design phase regarding temporal and behavioural implications of end-users and provides direction towards realizing widespread usage and therefore impact.

The works reviewed by El-Khoury et al. [2012] are an appropriate example of innovations with little to no diffusion strategy. There are a number of developed novel solutions to energetic and spatial comfort problems, however these solutions in the form of designs and prototypes do not explicitly consider how they will become solutions in the current framework of new or existing architecture. McCoy et al.'s concurrent commercialization index [2010, 222-243] would be a useful tool to apply to this research in the future.

7.3 Modelling Baseline

This study also validates COMSOL as effective modeling software for 3D energy balance problems where numerous layers of spectrally dependant transparent media (glazing and air) are involved. Work identified in the previous literature either dealt with these problems in 2D, or only considered a single layer of glazing and/or fluid in 3D problems - modelling of solar thermal collectors for example.

8. Further Work

8.1 Different Window orientations

This study was framed around a western building orientation. While this aided in uncovering some of the dynamic solar influence associated with the problem, certain orientations will benefit from various levels of control that others may not. Consider that a north facing window will receive little direct radiation in the GTA and therefore may be best suited to using only a static control for an OI system. A south facing window would receive maximum radiation and therefore would benefit from a fully passive OI system.

This would also help inform the question of whole-building feasibility for controlled OI systems, contributing to the overall diffusion strategy through a more relatable energy saving metric.

8.2 Design Iterations

One design option that was considered but not implemented is a dark surface color to increase the emissivity of the OI. This would allow for greater absorption of solar energy, providing quicker cavity heating, thereby increasing "open time" and improving the overall efficiency of the system. However, this increased cavity heating would add to the potential breakage and safety concerns associated with improper off-season use of interior rigid insulation systems cited in some of the literature [Garber-Slaght 2011, 15]]. In addition, the lag associated with movement of the system is unknown, and this extremely absorptive condition, may yield a design that operates in an unexpected manner or exacerbates the overheating-safety concerns. Future designs and research could address this design concept.

Non-residential buildings experience the same problems as homes. Future designs that can be effective in any number of building types may be worthwhile. These can include whole curtain-wall or window-wall OI systems that are present in many multi-unit residential buildings

(MURBs), institutional, and commercial buildings present in the GTA, and worldwide.
The educational aspect of relating indoor thermal well-being to windows, insulation and energy transmission concepts is another design consideration that may be worth incorporating into future research and design.

8.3 COMSOL Modeling

Future modeling work will address the outlined limitations in order to form more accurate models. Primarily these include; adaptive surface radiation according to the deformed geometry, and full length heating season studies.

Another limitation is that the theoretical control is modeled as activating instantaneously at 26°C for opening, when in reality, it would begin opening at 22°C and finish at 26°C. This may have additional impact on heat flux savings and should be incorporated into future models.

In addition, focusing on savings on a per-window basis does not provide an immediately relatable metric for assessing performance. Future modeling work should address the whole building as an energy model in greater detail.

8.4 COMSOL Post-processor Extensions

The surface temperature profile produced by the infrared camera reflects the temperature color plot produced in COMSOL quite well. There is some discrepancy between the window assembly and surrounding wall as the camera can only be calibrated to one surface emissivity at a time.

An element of this research that did not end up having its expected initial impact was the use of thermal imaging. However, it was this data that when compared with simulation values and animations provided effective learning and as well as best practice instructions for collecting data with thermocouples.

An extension of COMSOL's post processing plot capabilities may be valuable when combined with Infrared imaging software, to provide on the spot comparisons of simulated and calculated values. This may be especially valuable to building energy specialists who can reduce their time spent taking measurements on site, or crafting accurate simulations at other times.

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10. Appendix A – Heat Transfer Equations

Conduction

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p U \cdot \nabla T = \nabla \cdot (k \nabla T) + Q$$

[1]

where:

• ρ is the density - SI unit: kg/m^3

• Cp is the specific heat capacity at constant pressure - SI unit: $J/kg \bullet K$

• T is absolute temperature - SI unit: K

• u is the velocity vector - SI unit: m/s

• k is the thermal conductivity - SI unit: $W/\mathrm{m} \bullet K$

• Q is the heat flux by conduction - SI unit: W/m^2

Convection

$$h' = 5.62 + 3.91u$$

[2]

where:

• u is the velocity vector of air - SI unit: m/s

Solar Source Position

$$G_{ext.Bi} = F_{ext.Bi}(i_s) \cdot q_{0.s} \cdot FEP_{Bi}(T_{sun})$$

[3]

where:

• G_{ext} is the sum of source radiation contributions - SI unit: W/m^2

• B_i is the Biot number

• F_{ext} is the source view factor

• i_s is the incident radiation direction (unitless)

• $q_{0 \bullet s}$ is the source heat flux – SI unit: W/m^2

• FEP is the finite element package

The zenith and azimuth angles of the sun are converted into these direction vectors

X= North, Y= West, Z= Zenith

Radiation (surface to surface)

$$-n \cdot (-k\nabla T) = \sum_{i=1}^{N} \varepsilon_{Bi.u}(G_{Bi.u} - e_b(T)FEP_{Bi.u}\,(T)) +$$

$$\sum_{i=1}^{N} \varepsilon_{Bi.u}(G_{Bi.u} - e_b(T)FEP_{Bi.u}\,(T))$$

[4]

where:

• n is normal to a surface

• k is the thermal conductivity - SI unit: $W/\mathrm{m} \bullet K$

• T is the absolute temperature - SI unit: K

• ε is the surface emissivity (unitless)

• B_i is the Biot number

• subscript $_u$ denotes the upward side of a domain

• e_b is the blackbody emissivity

• FEP is the finite element package

• subscript $_d$ denotes the downward side of a domain

$$(1-\varepsilon_{Bi.u})G_{Bi.u} = J_{Bi.u} - \varepsilon_{Bi.u}e_b(T)FEP_{Bi.u}(T)$$

[5]

$$(1-\varepsilon_{Bi.d})G_{Bi.u} = J_{Bi.d} - \varepsilon_{Bi.d}e_b(T)FEP_{Bi.d}(T)$$

where:

- ε is the surface emissivity (unitless)
- B_i is the Biot number
- subscript $_u$ denotes the upward side of a domain
- G is the irradiance - SI unit: W/m^2
- J is the radiosity - SI unit: W/m^2
- e_b is the blackbody emissivity
- T is the absolute temperature - SI unit: K
- FEP is the finite element package
- subscript $_d$ denotes the downward side of a domain

$$FEP_{Bi}(T) = \frac{15}{\pi^4}\int_{C_{2/}(\lambda_i T)}^{C_2/(\lambda_{i-1}T)} \frac{x^3}{e^x - 1}dx$$

[6]

where:

- FEP is the finite element package
- B_i is the Biot number
- T is the absolute temperature - SI unit: K
- $\int$ is the integral of the temperature-radiation emission interaction

$$e_b(T) = n^2 \sigma T^4$$

[7]

where:

• e_b is the blackbody emissivity

• T is the absolute temperature - SI unit: K

• n is normal to a surface

• σ is the Stephan-Boltzmann constant

$$G_{Bi.u} = G_{m.Bi.u}(J_{Bi.u}) + G_{amb.Bi.u} + G_{ext.Bi.u}$$

$$G_{Bi.d} = G_{m.Bi.d}(J_{Bi.d}) + G_{amb.Bi.d} + G_{ext.Bi.d}$$

[8]

where:

• G is the irradiance - SI unit: W/m^2

• B_i is the Biot number

• subscript $_u$ denotes the upward side of a domain

• G_m is the mutual irradiance - SI unit: W/m^2

• J is the radiosity - SI unit: W/m^2

• G_{amb} is the ambient irradiance - SI unit: W/m^2

• G_{ext} is the sum of source radiation contributions - SI unit: W/m^2

• subscript $_d$ denotes the downward side of a domain

$$G_{amb.Bi.u} = F_{amb.Bi.u} e_b (T^4_{amb.Bi.u})\ FEP_{Bi.u}(T_{amb.Bi.u})$$

$$G_{amb.Bi.d} = F_{amb.Bi.d} e_b (T^4_{amb.Bi.d})\ FEP_{Bi.d}(T_{amb.Bi.d})$$

[9]

where:

- G_{amb} is the ambient irradiance - SI unit: W/m^2
- B_i is the Biot number
- subscript $_u$ denotes the upward side of a domain
- F_{amb} is the ambient view factor
- $e\ _b$ is the blackbody emissivity
- T_{amb} is the ambient temperature – SI unit: K
- FEP is the finite element package
- subscript $_d$ denotes the downward side of a domain