Passive Thermal Control for Window Insulation

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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 control. How can this best be performed to yield passive benefits such as solar heating?

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, 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. Simulation results of the concept reveal improvements that translate to reduced heat energy losses over the tested normal static, and more commonly used – daily cycle systems.

Keywords: Radiation, Solar, Window, Insulation, Control

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].

Windows are a thermal weak point in the building envelope. 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. There are energy (and thus environmental), and financial consequences associated with relying on active systems to meet the dynamic heating and cooling loads of the Canadian climate.

1.1 Operable Insulation

One effective technique for limiting window heat loss, involves application of additional movable insulation to conserve energy in the heating season. This type of system is often designed to be used exclusively at night, when neither views, nor solar radiation are able to be transmitted through the window.

There are several drawbacks to most operable insulating (OI) methods that have not been addressed even to this day. The main drawback, is that these systems are often in static configurations and require manual user operation. This can lead to a number of problems, including window overheating - a cause for potential damage [Garber-Slaght, 2011], and more importantly; it can form a restriction to passive building heating from potential solar heat gains through the glazing.

2. Theory

A superior control scheme would not only alleviate the concerns associated with manual human operation errors (i.e. forgetfulness or laziness) but it also presents an opportunity to optimize the energy balance through the window.

A control and its mechanism have been theorized and produced with the aid of rapid-prototyping technology (RPT). The control responds to ambient temperature conditions to ensure that the insulation is partially removed when the incoming energy exceeds that which is being lost through the bare window. This creates a direct-gain, passive solar heating system.

The control has been designed for use in the heating season only. The system is essentially a rigid insulation OI, with opening slats that mimic conventional interior shutters. See Figure 1 for a section view of the opening system

The research question is: will an operable insulation system with this highly responsive control mechanism, yield noticeable improvement over a conventional, static or daily-cycle, manual control system?

3. Methodology

This research has a mathematical modeling component, as well as an experimental component that provides primary data to inform the simulation. Infrared imaging was used first, to provide visualization for the problem (see Figure 2).

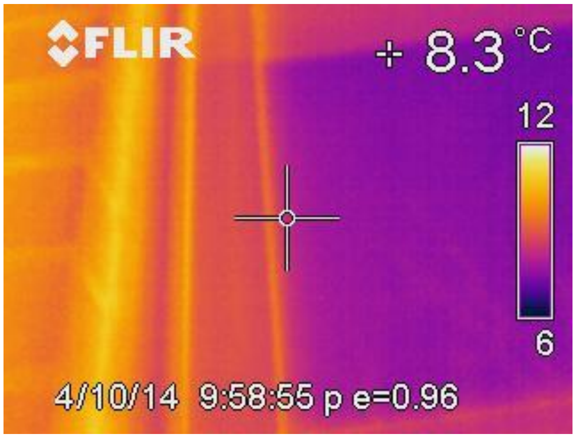

Figure 2. Infrared Imaging

Use of imaging was abandoned for thermocouples which provide a better depth of information (i.e. measurement of numerous surfaces of the assembly) They are also superior to imaging as thermocouples have the ability to collect a wider range of data with the use of a data logger.

Thermocouples were arranged in a fashion outlined in Figure 2 below.

Figure 2. Windows, part of the OI system, and taped thermocouples used in the experiment in a test-home

Data was collected for approximately two weeks from the nights of April 10, to April 25, 2014 at intervals of 10 minutes.

Solar irradiance and air temperature data were concurrently collected from a local weather station.

4. Use of COMSOL Multiphysics

The conjugate heat transfer with radiation, and deformed geometry (ALE) modules were used in forming the model.

For consistency, results are taken at the 'room-window plane'.

4.1 Model Description

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 construction were not modeled, as only the exterior surface is of relevance for radiation effects. The wall’s thermal conductivity, density and heat capacity were specified as average values for a Canadian, conventionally code-built, brick clad, 2x6” construction.

Input of relevant material properties of the construction components are based on data already incorporated into the COMSOL material database and from other sources [ASHRAE, 2009]

4.2 Heat Transfer and Solar Radiation

Meteorological functions derived from the experimental data were incorporated as global functions. The heat transfer in both solids and fluids account for the conduction and convection effects.

The external radiation was specified as a solar source acting on the real geographic location and orientation of the home. Due to the research gathered regarding most modern window assemblies [EWC, 2011], overall radiation was split into ambient (long-wave) and solar (short-wave) bands. This allowed for accurate representation of window transmission characteristics.

The concept of sol-air surface heating was applied to the problem [Hutcheon, 1983]. The insulation, though not exposed to the exterior air, is the first surface encountered in the window assembly, that is opaque to short-wave radiation. Hence the correction is appropriate at these boundaries.

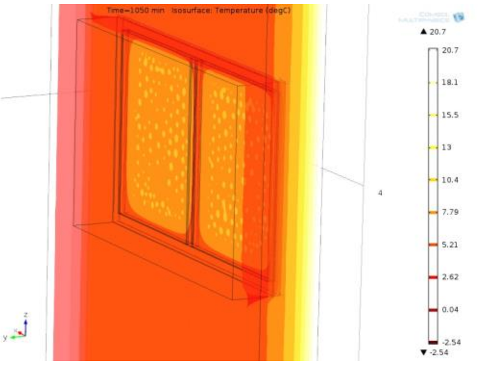

Figure 3. Surface Temperature Plot

4.3 Moving Mesh (ALE)

The operable insulation control is calibrated to an average heating set-point of 26°C. This limits the potential for conduction/convection losses as the insulation opens.

In the model, the exterior facing boundary of the movable components of the insulation are specified as a component coupling measuring the average temperature value as seen in Figure 4 below.

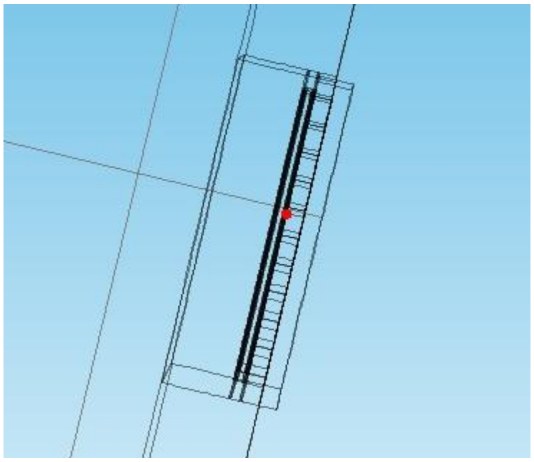

Figure 4. Component Coupling Location – Exterior of Insulation

This is then linked to the prescribed domain displacement of the movable components (pictured in blue in Figure 5) in both the z and y directions.

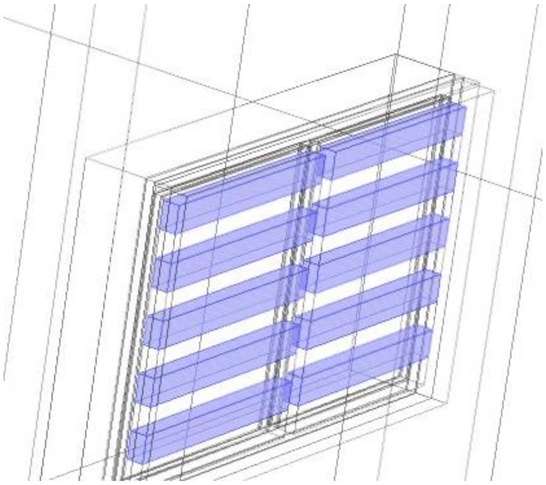

Figure 5. Domains with Prescribed Displacements (the Moving "Slats")

5. Mathematical Model

5.1 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

5.2Convection

$$h' = 5.62 + 3.91u$$

[2]

where:

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

5.3 Solar Source Position

$$G_{ext.Bi} = F_{ext.Bi}(i_s) \cdot q_{0.s} \cdot FEP_{Bi}(T_{sun}) \quad [3]$$

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)
- $q_{0.s}$ 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

5.4 Radiation (surface to surface)

$$-n \cdot (-k\nabla T) = \sum_{i=1}^{N} \varepsilon_{Bi.u}(G_{Bi.u} - e_b(T)FEP_{Bi.u}(T)) + \sum_{i=1}^{N} \varepsilon_{Bi.u}(G_{Bi.u} - e_b(T)FEP_{Bi.u}(T)) \quad [4]$$

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

$$(1-\varepsilon_{Bi.u})G_{Bi.u} = J_{Bi.u} - \varepsilon_{Bi.u}e_b(T)FEP_{Bi.u}(T)$$
$$(1-\varepsilon_{Bi.d})G_{Bi.u} = J_{Bi.d} - \varepsilon_{Bi.d}e_b(T)FEP_{Bi.d}(T) \quad [5]$$

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

$$FEP_{Bi}(T) = \frac{15}{\pi^4}\int_{C_2/(\lambda_i T)}^{C_2/(\lambda_{i-1}T)} \frac{x^3}{e^x - 1}dx \quad [6]$$

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

$$e_b(T) = n^2\sigma T^4 \quad [7]$$

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

$$G_{Bi.u} = G_{m.Bi.u}(J_{Bi.u}) + G_{amb.Bi.u} + G_{ext.Bi.u}$$
$$G_{Bi.d} = G_{m.Bi.d}(J_{Bi.d}) + G_{amb.Bi.d} + G_{ext.Bi.d} \quad [8]$$

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

$$G_{amb.Bi.u} = F_{amb.Bi.u}e_b(T_{amb.Bi.u}^4)\,FEP_{Bi.u}(T_{amb.Bi.u})$$
$$G_{amb.Bi.d} = F_{amb.Bi.d}e_b(T_{amb.Bi.d}^4)\,FEP_{Bi.d}(T_{amb.Bi.d}) \quad [9]$$

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

6. Results and Discussion

The experimental results confirm the effectiveness of a static OI system for reducing heat loss in the Canadian climate. Figure 6 shows the measured-calculated heat flux through the bare window (dotted line) and static OI window (solid line).

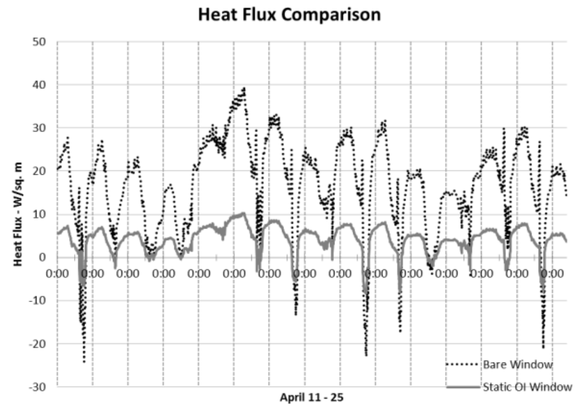

Figure 6. Comparison of Bare Window (dotted) to Static OI Window (solid)

Figure 7 shows the comparison of measured surface temperature results (dotted line) and the simulated COMSOL results (dashed line) at the same location of the exterior of the insulation.

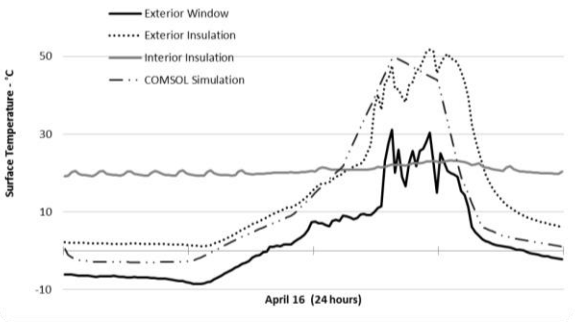

Figure 7. Comparison of COMSOL (dashed) and Experimental (dotted) results with the interior and exterior temperatures

The OI simulated with night-control or full-control has improvements on par with the measured values for a static system (see Figure 6). Upon closer, daily inspection, inefficiency with the night-control scheme's timely opening and closing is uncovered that is not associated with the full-control. Compare the small peaks in Figure 8 with the same points in Figure 9.

These values were derived from a cut-point positioned at roughly the centre of the bare, and OI window.

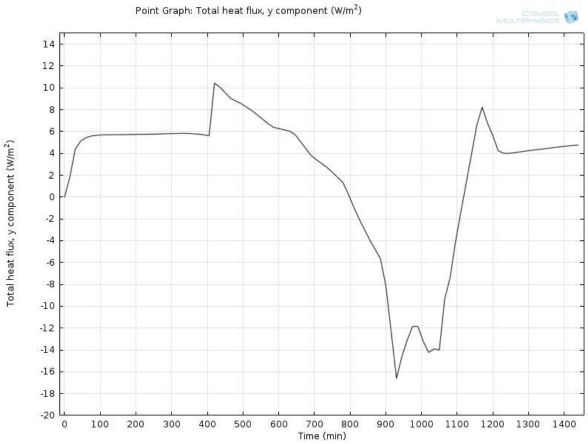

Figure 8. Heat Flux – Night Control (April)

Figure 9. Heat Flux – Full Control (April)

Similar phenomenon are seen during the deep heating season in December (compare Figures 10 and 11 below).

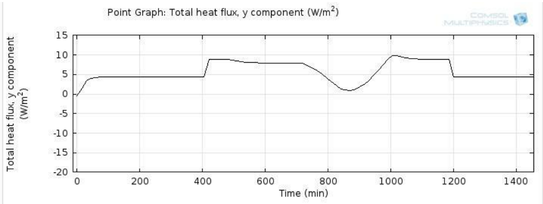

Figure 10. Heat Flux – Night Control (December)

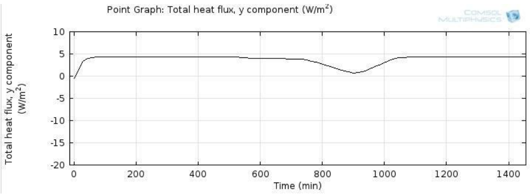

Figure 11. Heat Flux – Full Control (December)

7. Conclusions

Integrating results of the curves reveal improvements of about 1333 J/m^2 in spring and 2335 J/m^2 in winter.

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 about 28-40%. Surprisingly, a static system can potentially 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?

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.

8. References

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9. Acknowledgements

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