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Thermal 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 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 timely control of solar thermal energy input, and building thermal energy output with the use of operable window insulation is investigated during the heating season in the local Toronto climate.

This is done through a combination of 3D finite element mathematical model and field performance tests. Model results and field tests reveal an energy imbalance attributed to unpredictable solar gains and spectrally-dependent emissivity of materials. Simulation results of the daily control show little improvement over use of a static system for a western building façade. The negligible difference versus a static system is attributed largely to human-error deficiencies associated with timely controls.

1. Introduction

1.1. Background

Building energy use accounts for roughly 60% of all consumed energy, and roughly 40% of this energy is consumed for space heating. This percentage increases for climates with longer heating seasons and more extreme winters such as Canada, Russia, and northern Europe [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 roofs due to their low R_{SI} value.

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 outdoor environment.

Unfortunately, after possible use of passive energy design strategies applied to building envelopes, designers and occupants turn to active heating and cooling systems to regulate the indoor environment. Popular examples of active systems – which often rely on a non-renewable energy source – include: natural gas furnaces, electric baseboard heaters, and refrigerant air conditioners. These systems are the primary means to address changes to the thermal environment over time. Many of these changes are predictable based on historical data, such as daily or seasonal temperatures. Energy and financial consequences are associated with reliance on active systems to meet dynamic heating and cooling loads. These are validated and addressed in part through government legislation as well as a number of standards that are meant to respond to recent 'green' market forces. Examples include municipal building codes, and the LEED and EnerGuide building energy rating systems.

1.2. The problem

The purpose of this paper is to develop an accurate energy model to inform a feasibility study and to identify the current limitations of control of energy transmission through operable window insulation. There are two control systems in common use for operable insulation; seasonal-static systems and manual control systems. Each comes with their own specific challenges and limitations.

The application of night-time (timely manual control) to operable insulation 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 [2]. However

Abbreviations: OI, operable insulation; TIM, transparent or translucent insulation material(s); XPS, extruded polystyrene; GTA, greater Toronto area region.

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Nomenclature

ρ	the density (kg/m$^{3)}$
C_p	the specific heat capacity at constant pressure (J/kg K)
T	absolute temperature (K)
u	the velocity vector (m/s)
λ or k	the thermal conductivity (W/m K)
R or R_{SI}	is the thermal resistance (M^2 K/W or h ft^2 °F/Btu)
Q	the heat flux by conduction (W/m^2)
G_{ext}	the sum of source radiation contributions (W/m^2)
Bi	the Biot number
F_{ext}	the source view factor
i_s	the incident radiation direction
$q_{0\,s}$	the source heat flux (W/m^2)
FEP	the finite element package
n	normal to a surface
ε	the surface emissivity
e_b	the blackbody emissivity
subscript u	denotes the upward side of a domain
subscript d	denotes the downward side of a domain
G	the irradiance (W/m^2)
J	the radiosity (radiant existence) (W/m^2)
σ	the Stephan–Boltzmann constant
G_m	the mutual irradiance (W/m^2)
G_{amb}	the ambient irradiance (W/m^2)
F_{amb}	the ambient view factor
T_{amb}	the ambient temperature (K)

there is an inherent drawback with manual control of systems – in order for any OI system to be effective, it needs to be appropriately operated. Building heating and cooling loads are constantly 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. Shading from clouds and the surrounding environment can reduce incident energy by as much as 23% for clouds and up to 100% for surrounding opaque objects [3]. Human error (read *forgetfulness* or *laziness*) is a notorious opponent to efficiency of systems that rely on manual operation and propensity toward it should be minimized or altogether eliminated. A static system also has an inherent limitation; in that it is rather permanent. While this ensures that heat loss through the window is limited, it affects normal desirable window functionality such as admission of daylight, solar radiation and visual information.

2. Literature review

Windows and other wall penetrations have poor insulating properties as compared to other building envelope components, and often require extra mitigation efforts. Pragmatic methods have been as simple as the use of curtains, quilts, or applications of other dressings to the window to limit heat loss. These all qualify as OI. Modern systems fall into two broad categories; interior and exterior systems. Exterior systems often suffer from a lack of control as they are less accessible than interior systems, while interior systems often experience more condensation issues [4,5].

Research focusing on applications of various OI systems currently exists. Papers such as those of Alsaad [6] and Liu et al. [2] deal with on-site and laboratory tests of static and night-control systems and provide direction for experimentation. The state of the art material for use in a static system is transparent or translucent insulation materials (TIMs). They allow for some transmission of visible light and provide additional insulation value. These would be classified as non-view systems however, as views are often distorted due to frequent use of translucent materials. Presently, application of this technology to *existing* windows is not recommended as there are elevated concerns with incompatibility, overheating and breakage [8]. In addition, such systems are often not feasible as aerogel and other TIMs are recent innovations that are more expensive to produce [6,7]. Even without use of TIMs, there are drawbacks to unmonitored use of any static OI system that can lead to a number of problems, including unventilated window overheating – a cause for potential damage [9]. More importantly, in a similar fashion to conventional static OI systems, TIMs forms some level of restriction to passive building heating from potential solar heat gains through the glazing. Exploration of insulation control systems is far less developed throughout the literature.

Thermal-energy modeling of windows and various treatments has also been performed. Modeling methods are numerous but the majority of models incorporate CFD analysis in 2 or 3 space dimensions. An accurate model of solar radiation is vital when considering heat transfer in architecture and incorporates intermediate factors, such as ground albedo, view factor calculations, and glazing transmission characteristics [9].

These areas of research provide the basis for realistic modeling as well as 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 adaptive opportunities for buildings in general.

3. Objectives

There is a gap in knowledge and application of solar energy resource use – especially with regard to efficient utilization over time. Solar radiation varies in quantity and quality by location but also in time, and in ways that are not entirely predictable [3]. Little effort is put into maximizing the solar resource over shorter time periods, especially where buildings are concerned. Instead, passive heating/cooling designs are based on an optimal yearly or seasonal value (like roof overhang distances for example).

The goal of this paper is to identify the problems with passive heating and heat energy conservation through operable window insulation. This requires a strong theoretical understanding of the physical energy balance associated with windows, and various additional OI treatments and methods of control as framed in the current literature.

The major research question is; will a static or timely manual control OI system be feasible for residential use in the local greater Toronto area (GTA) climatic region?

4. Research methodology

The experiment was developed to better understand the thermal interactions between room, windows, treatments, and the outdoor environment. Design, construction, and installation of a prototype static system aided in discovering construction flaws, and tolerances which may affect proper installation (i.e. air sealing). In order to come to a baseline of energy performance for the mathematical model, the physical test methodology did not involve any actual removal/addition of the insulation during the two-week period. Opening/closing are however, modeled and simulated.

High resolution weather data is obtained from the University of Toronto weather station. It is used for the purpose of model validation.

4.1. Unit design

A customized OI system was created for experimental testing (see Fig. 1). It consists of two 50 mm deep frames and inserts