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Control strategies for dynamic insulation materials applied to commercial buildings

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ABSTRACT

This paper evaluates the potential heating and cooling energy use and cost savings associated with improved controls of dynamic insulation materials (DIMs) when used in multilayered wall assemblies for commercial office buildings. Using a genetic algorithm (GA) based optimization technique, optimum R-value settings are identified for the DIMs throughout the year. These optimal R-value settings are selected to maximize energy cost savings when compared to traditional static insulated wall systems. It is found that optimal control settings for DIMs depend on several factors including building design and operation strategies as well as climatic conditions. Moreover, the optimal settings were found to depend on the orientation of exterior walls and well as the climatic conditions. Specifically, the analysis results indicate that north-facing walls are more active and frequently have to change their R-value in order to minimize the office building energy use and cost. When optimally controlled, DIMs could save up to 17% of annual heating and cooling energy costs for US office buildings.

1. Introduction

Building energy efficiency can be improved by using both passive and active strategies [1]. Strategies to improve the energy performance of heating, air conditioning and ventilating (HVAC) systems, lighting systems, and appliances are typically considered as active strategies. Measures and technologies utilized to improve the performance of building envelope systems are generally be considered as passive energy efficiency strategies. Several studies have been conducted and reported to assess the energy saving potential of passive strategies. In particular, it was estimated that as much as 35% to 47% of peak cooling demands could be reduced in sub-tropical climates like Hong Kong through the use of enhanced building envelope systems [2]. Moreover, a study in Greece, indicated that the improvement in thermal insulation and low infiltration strategies alone can reduce energy consumption by up to 40% [3].

Heating and cooling demands are mainly governed by heat transmission through building envelope systems and physical material properties such as thermal conductivity, specific heat, and density. One of the main strategies for improving energy efficiency of building envelope systems is to apply insulation materials with high thermal resistances. In particular, insulating materials such as mineral wool, polyurethane, expanded and extruded polystyrene with high thermal resistances (i.e., low thermal conductivity values) are typically used. Recently, new technologies for high thermal insulation systems have also been introduced for building applications including vacuum insulation panels (VIPs), gas insulation panels (GIPs), and Nano insulation materials (NIMs) [4]. However, concerns remain regarding the long term durability and reliability of these insulation materials. Generally, a high thermal resistance insulation can be effective in reducing heat transfer through building envelope components (i.e., walls, roofs, and floors) especially for extreme climates (i.e., cold or hot climates). However, and in most climates with seasonal variations, building envelope systems with high R-values can be beneficial for one season but may not necessarily be beneficial for other seasons [4]. In cold climates, for instance, high thermal insulation in walls and/or roofs could potentially increase building thermal loads during mild periods of the year when it may be beneficial to let heat that is trapped indoors to escape outdoors. A number of strategies exist to release stored heat with variable degree of effectiveness such as phase change materials (PCMs) and natural ventilation through opening windows. The use of Dynamic Insulation Materials (DIMs) has been recently proposed to allow switchable thermal resistances features to be integral parts of the building envelope systems [4]. While an initial work for the effectiveness of DIMs has been completed to assess their potential in reducing heating and cooling loads in buildings

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in a wide range of climatic conditions, no analysis has been carried to assess the best control strategies to switch their properties [4].

The study outlined in this paper briefly describes the application of DIMs to commercial buildings and assesses their energy savings potential when they are optimally controlled. The analysis is carried out using a RC-network based energy simulation environment developed by Park et al. [4]. The capabilities of the simulation environment have been enhanced to include genetic algorithm (GA) based optimization algorithms in order to determine the best settings for operating DIMs applied to various building envelope components under wide range of climatic conditions. In this paper, an overview of control strategies specific to DIMs is first outlined. Then, GA-based optimal controls are defined to switch the settings of DIMs for a prototypical office building. Select results are finally discussed to assess the performance of optimally controlled DIM under various design, operating, and climatic conditions.

2. Optimal controls for DIMs

Several studies have been theorized on the options to develop dynamic properties of construction materials that can be used in buildings. But most of these technologies have been mostly applied to smart windows rather than opaque envelope walls. Only recently, a new study has proposed the use of Dynamic Insulation Materials(DIMs) for opaque envelope walls [4]. Conceptually, the DIM is to be constructed as a rigid cellular panel that can be placed within the external building construction assembly wall cavities as a replacement of traditional static insulation materials. The bulk thermal conductivity of the DIM is then tailored by the introduction of inert gases with variable conductivities (e.g. CO2, N2, He) thus affecting the heat transfer through the building envelope [4]. Initially, it has been envisioned to vary the DIM thermal properties (i.e., thermal conductivity and ultimately the thermal resistance of the building envelope) using a simple 2-Step control algorithm [4].

Fig. 1 depicts the basic operation of 2-step control strategy to vary the thermal resistance for a DIM wall. The controller first identifies the direction of heat flow through the building envelope system by determining the temperature gradient between the external surface wall temperature (Tso), internal surface wall temperature (Tsi), and the internal wall temperature(Ti). Based on the heating/cooling set point temperatures, the controller then determines the best DIM R-value (high or low) based on the operation mode (i.e., heating or cooling). For example, in the cooling season when Tso is higher than Tsi, DIM increases its thermal resistance (i.e., R-value) so that it reduces heat gains through the exterior walls. Similarly, when Tso is lower than Tsi during the cooling season, the R-value of DIM is reduced to release heat from the indoors to the outdoors through the walls. In addition to Tso and Tsi, Ti is another valuable parameter that can help in determining the direction of the wall heat flux as illustrated in Fig. 1. Since solar radiation incident on exterior wall surface varies with orientation, each wall may have to be separately controlled.

Using this simplified control strategy, it has been shown that without any internal loads this technology has the potential to save 32–39% cooling energy consumption of residential building located in Golden, CO, and Madison, WI [4]. In particular, it was noted that DIMs can be especially effective in reducing building cooling thermal load and energy use. However, it is found that the performance of DIMs is dependent on several factors including ambient conditions, internal heat gains, and building envelope design features. Specifically, the energy savings obtained when applying DIMs were found to be higher when lower values of both internal gains and window to wall ratios (WWRs) are considered. While lower internal gains and WWRs are prevalent for small residential buildings, heat gains from lighting, equipment, and people are generally significant for commercial buildings. Moreover, windows sizes and thus WWRs are often selected to be large for office buildings to enhance daylighting features and connections with the outdoor environment. The simple 2-Step control algorithm which has been used to control the operation of DIMs when applied to residential buildings might hence not be the best control strategy for DIMs when applied for commercial buildings.

To explore different control options for DIMs, a brute force optimization analysis technique is initially considered to determine the best schedule for DIM settings associated to each of the building walls. However, this technique is computationally very inefficient. For instance, when using 2-value settings of thermal resistances for DIMs (i.e. high R-value and low R-value) and an hourly switch schedule for only one wall, over 16 $^*10^6$ (i.e., 2^{24}) individual combinations of settings have to be evaluated for a single day using the brute force optimization method. While, several other more efficient optimization techniques can be considered to determine the optimum resistance settings for all the DIMs applied to the building walls, Genetic Algorithm (GA) optimization technique has been selected based on its ease of implementation and its ability to effectively optimize design and operation of various building energy systems. Indeed, GA-based optimization techniques have been successfully used to select building shapes [5], envelope features [6], and HVAC systems [7]. For instance, Bichiou and Krarti [8] have applied GA-based optimization to select energy efficiency measures for both envelope and HVAC systems to minimize life-cycle costs for operating commercial buildings.

Optimization GA-based techniques can be applied to both constrained and unconstrained optimization problems and utilize a natural selection process that mimics biological evolution [9]. Specifically, GA optimization iteratively selects a set of individual solutions from a current generation using probabilistic techniques. These selected individuals are then defined as parents to produce children for the next generation. This selection process ensures that GA approaches the global optimum with minimal risks to get stuck on a local optimum. Over successive generations, the population evolves towards the optimal solution [9]. In this study, the objective function and constraints for the GA-based optimization analysis considered for controlling the DIM settings is stated by Eq. (1):

$$f = min\left(\sum_{0}^{24hrs} E_{cooling} * \mathrm{rate}_{cooling} + E_{heating} * \mathrm{rate}_{heating}\right) \tag{1}$$

$$for : kl \leq k \leq ku$$

Where,

- k- thermal conductivity values to be set for the DIM for all the building walls
- kl, ku –lower bound and upper bounds of thermal conductivity values
- $rate$ $_{\mathrm{cooling,heating}}$ - utility rates for electricity and natural gas, respectively
- $E_{cooling}$- Energy use associated with the cooling system
- $E_{heating}$- Energy use associated with the heating system

The optimization objective function of Eq. (1) is set to minimize the total building heating and cooling energy cost during one day by varying the thermal conductivity value (and thus R-value) settings the DIM for each building wall separately. The thermal conductivity values of each wall have an upper and lower bounds that have been set for the optimization analysis carried out in this study to be 2.0 W/m.K and 0.032 W/m.K, respectively [4]. For a fixed thickness of 0.075 m (3-in) insulation, the upper and lower bounds of thermal conductivity correspond to the DIM layer having a low resistance of 0.04 m^2K/W to a high resistance of 2.37 m^2K/W. The GA-based optimizer hence, analyses all potential DIM layer R-values between 0.04 m^2K/W and 2.37 m^2K/W to identify the best DIM settings for