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Numerical modeling of thermal behaviors of active multi-layer living wall

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ABSTRACT

The paper numerically models the thermal behaviors of multi-layer living wall. The aim of this study is to identify the most efficient wall configuration according to indoor and outdoor climate conditions by using a new simulation tool developed using Matlab and Simulink. The simulation tool is created to evaluate both conventional façade systems and those integrated with phase change materials (PCMs). The model is validated using experimental results from the literature for the multi-layer PCM-enhanced wall. The ventilated cavity wall model is also verified using TRNSYS "TYPE36", a well validated and respected model for simulating thermal storage wall. The location within the wall assembly, the orientation and the optimal thermal properties of PCM's are then analyzed using the tool. The validated multi-layer wall system is further integrated with a full-scale building model with a genetic algorithm optimization method. The results show that an optimized active multi-layer living wall system can allow 27–38% of reduced heating energy consumption while avoiding thermal discomfort.

1. Introduction

Most developed countries such as US aim to have all new buildings reach the nearly zero-energy building (NZEB) standards in the next 20–30 years. This demands a whole package of NZEB-related technologies to be developed and applied in all the technical and practical aspects, ranging from building energy supplies (e.g., renewable sources) to high performance building systems. Among these, the improvement of building envelope performance is one of the most cost-efficient solutions for reaching NZEBs.

Studies are found in literature that optimized building envelopes in natural weather and living conditions, which however limits its suitability for air conditioned environments [1]. The study of building envelope needs to consider both elemental selection (e.g., material performance) and system integration and optimization. Many studies were carried out to regulate better heat transfer in building envelope without increasing the mass. For instance, Cheung et al. [2] performed a concrete study of building envelope and its impact on building energy usage. The paper studied high-rise apartments in the hot and humid climate of Hong Kong. They implemented an envelope constituted of extruded polystyrene (EPS) thermal insulation in the walls, white washing external walls, reflective coated glass window glazing, and external shading to all the windows. They found that these strategies allow an energy saving of 31.4% and peak load savings of 36.8% from the base case. In a different investigation, Chan et al. [3] used the DOE-2 building energy simulation tool to study the thermal performance of a building envelope in Hong Kong. Their building envelope design saved around 35% and 47% of total and peak cooling demands, respectively. Balaras et al. [4] found that thermal insulation in walls, roof and floor reduced building energy consumption by 20–40% and by 20% using low infiltration strategies. In the same study, the authors noticed that external shadings and light-colored roof and external walls reduced the space cooling load by 30% and 2–4%, respectively. Many others numerical studies has been done on building specially on heat and mass transfer through a typical building envelope [5–7], taking into consider of heat conduction, convection, radiation, and humidity transfer mechanisms.

Nowadays, important improvement and progress on sustainable materials research has been observed, especially for building envelope applications due to the large building energy use. As an example, the Fiber-reinforced plastic is one of the best composite materials used in wall and roof construction [8]. In the UK, sustainable earth materials are used to upgrade historical constructions,

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Nomenclature

T_{amb}	ambient air temperature
$T_{environment}$	air temperature, sky temperature, and ground temperature
T_{avg}	average air temperature inside the cavity
T_{Top}	air temperature at the top of the cavity
T_{Bottom}	air temperature at the bottom of the cavity
T_{go}	exterior node glazing temperature
T_{gi}	interior node glazing temperature
T_{wo}	exterior wall surface temperature
T_{wi}	interior wall surface temperature
T_{node}	internal node temperature
b_{Gap}	cavity depth
h_{LWR}	long wave radiative heat transfer coefficient
$h_{Rad_{cavity}}$	radiative heat transfer coefficient inside the cavity
$h_{con_{cavity}}$	convective heat transfer coefficient inside the cavity
h_{c_o}	outdoor convective heat transfer coefficient
h_{c_i}	indoor convective heat transfer coefficient

such as unfired clay bricks, straw-clay mixture and straw bales. Note that these materials comply well with the UK building regulations for U-value [9]. Other materials are applied for thermal energy storage: sensible, latent and thermochemical energy storage [10]. Among these materials, the phase change materials (PCM) show great potential and may be widely used in buildings envelope in the future. PCMs absorb or release latent heat when they undergo a phase change from one physical state to another. The phase change can occur in different forms notably solid–solid, solid–liquid and vice versa. The aim of using latent heat storage is to reduce the temperature fluctuation, especially the fluctuation due to incident solar radiation loads, as studied by different numerical investigations [11–13]. Some of these materials provide more design flexibility [14] (solid–solid PCMs) while others are more economically attractive (solid–liquid PCMs) [15].

Reducing the energy demand of buildings through efficient envelopes should be a priority for all NZEB projects. The design of efficient building envelopes is fundamental and has to be performed before integrating renewable energy systems and maximizing the efficiency of mechanical systems. Using advanced energy analysis tools, building envelope can be optimally designed with an ultimate goal of reaching NZEB. For this purpose, this study introduces an advanced design procedure using a developed simulation tool to model and optimize different configurations of envelope materials and layouts. This simulation tool developed under Matlab and Simulink environment will select and provide data concerning several active envelope configurations that can be used and compared in experimental studies. The method can also be used to compare building alternatives with different materials in order to obtain the optimal choice of envelopes and quantify the effect of climate change on buildings in accordance with the optimal conditions of comfort and energy use.

The simulation tool and its inherent models are described first. Following that, different designs of envelope using phase change materials and ventilated cavities are studied numerically and results are compared with experimental data from the literature. Once the envelope model is validated and optimized, a genetic algorithm (GA) based optimization has been developed to couple the wall simulation model with a whole building simulation program.

2. MATLAB/SIMULINK and application for modeling building performance

MATLAB is a high-performance language for technical computing [16]. It is a powerful package integrated with huge functions. MATLAB is becoming a standard programming language used by various scientific groups. It is progressively improved with many toolboxes developed for many applications. In MATLAB environment, a standalone graphical user interface (GUI) based on MATLAB commands can be built. Using this approach, the GUI can be designed for a specific model. Alternatively, SIMULINK can be used. SIMULINK is an add-on to the MATLAB environment with a graphical user interface (GUI) for modeling dynamical systems. It has many built-in functions, ready-made modules and library of toolboxes.

Many successful standalone as well as complex system models have been developed using SIMULINK. For building applications, SIMULINK is primarily used for modeling HVAC systems and controls [17–22]. Other research groups have developed comprehensive libraries for modeling energy and hygrothermal performance of full scale buildings. Examples include HAMLab developed in Eindhoven University of Technology [23] and International Building Physics Toolbox (IBPT) developed jointly by a team from Chalmers University of Technology and Technical University of Denmark [24]. Others have developed simplified zones too [25–28]. SIMULINK has provided a flexible modeling framework for simulating building performance and its systems. The package is used in this work due to many reasons such as the flexibility, graphical capabilities and data visualization. In addition, it can be used for co-simulation with many building simulation programs such as EnergyPlus, TRNSYS and ESP-r. Hence, it is considered as a framework for this work.

2.1. Development of "AdvFacSy" Toolbox in SIMULINK

Advanced façade systems are becoming important architectural elements in modern buildings. While many façade systems are installed for architectural reasons, they can be utilized to perform multiple functions such as heat storage using PCM-enhanced components for example. The mechanism of heat storage, its transfer and transport involves complex physics. This complex physics is phenomenal and difficult to model with the state of the art whole-building simulation tools. Therefore, the overall goal was then to provide a framework tool that can be easily used to achieve this task. Advanced Façade Systems "AdvFacSy" is developed for this purpose using SIMULINK environment. In order to make it a self-sustained tool, the intended standalone models need additional supporting utilities and modules that provide boundary conditions. For example, weather data module that reads typical weather data files such as EnergyPlus weather format (EPW) is needed. In addition, solar radiation model is mandatory to calculate the solar radiation on tilted surfaces. Fig. 1 illustrates the concept of AdvFacSy in SIMULINK. The Simulink modules call MATLAB files that are located under subroutines folder. The folder contains many supplementary files to provide necessary information such as materials library and weather files or performs calculations such as mesh functions, solvers and other general functions for calculating mass flow rate, convective heat transfer coefficients etc.

2.1.1. Weather data reader

The weather data is available in raw data formats for many years. The raw data is not suitable for building simulation programs. A typical weather year, representing many years of weather data, has to be selected for the energy analysis. Many typical weather data sets are internationally recognized for use in detailed energy simulation programs. Well known weather data sets are available for