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A semi-dynamic model of active pipe-embedded building envelope for thermal performance evaluation

Qiuyuan Zhu [a,b], Xinhua Xu [a,c,*], Jiajia Gao [a], Fu Xiao [c]

[a] Department of Building Environment & Energy Engineering, Huazhong University of Science & Technology, Wuhan, China
[b] Wuhan 2nd Ship Design and Research Institute, Wuhan, China
[c] Department of Building Services Engineering, The Hong Kong Polytechnic University Kowloon, Hong Kong, China

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ABSTRACT

Active pipe-embedded building envelope is a new kind of pipe-embedded building external wall/roofs. Usually, pipes are embedded in the wall slab or roof slab to allow water circulating in these pipes for heat transfer. Low-grade energy sources can be used for this structure since the enlarged heat transfer surface between the slab mass and water in the pipe allowing for substantial heat flow for relatively small temperature difference. This structure may reduce building cooling/heating load and improve indoor thermal comfort by intercepting the heat/coolth from the ambient air to indoor space. This paper presents a semi-dynamic model of this structure for thermal performance evaluation for system design or indoor environment control etc. This semi-dynamic model is a coupled model. The first part is a simplified dynamic RC model (i.e., resistance and capacitance model). The heat transfer along the width of this structure can be predicted easily by the RC model. The second part is a classical *NTU* model for evaluating the heat transfer along the pipe and total heat transfer on both surfaces of this structure. A CFD model is developed to act as a virtual experimental test rig to simulate the thermal characteristics of this structure. The simulated results are used to validate this semi-dynamic model and its performance prediction.

1. Introduction

It is a common concern that energy is in short supply and the building energy consumption is increasing in the world. In China, building energy consumption is also increasing every year, and consumes about 30% of the yearly end energy use [2]. Air conditioning energy consumption is the main part of the building energy consumption. The energy consumption of air conditioning (usually using the high grade energy) is used to remove the cooling/heating load for keeping the required indoor environment. Reducing the heat transfer through building envelope is one of the means to reduce the cooling/heating load. Conventional means are to change the construction material, increase the thickness of the external wall, use phase change materials (PCM), or directly install insulation on the opaque building envelope, etc.

Active pipe-embedded building envelope is a new building envelope structure. It is an external wall or roof with embedded pipes and can utilize circulating water in the pipe to remove heat/coolth inside the structure directly [22,26]. Active pipe-embedded building envelope has the similar advantages with pipe-embedded floors or ceilings for radiant heating or cooling, which may significantly enlarge heat transfer surface between the structure mass and the water in the pipe for allowing substantial heat flows even for relatively small temperature difference between the mass and water [3,4,19]. One of the big advantages is that it can use renewable energy sources to trap heat or coolth from outdoor to indoor space through the pipe water to reduce indoor cooling load or heating load. These low-grade energy sources may be groundwater, the cooling water produced by cooling towers, and geothermal energy produced by the ground-coupled heat exchanger system, etc. [11,12,23]. From this point, active pipe-embedded building envelope is different from the pipe-embedded floor and pipe-embedded ceiling (usually called as thermally activated building systems).

Active pipe-embedded building envelope has been used for many actual building envelopes in the world. An air-conditioned office with a cool roof system located within an industrial

* Corresponding author. Department of Building Environment & Energy Engineering, Huazhong University of Science & Technology, Wuhan, China. Tel.: +86 27 8779 2165x403; fax: +86 27 8779 2101.
E-mail address: bexhxu@hust.edu.cn (X. Xu).

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building in Rome is analyzed by Pisello et al. [13]. The results show that this system can reduce cooling loads and improve cooling system efficiency. The efficient cooling and heating of an office building with the active pipe-embedded building envelope (called thermally-active building system in the paper) in UK is presented by Babiak [5]. IDOM Madrid headquarter building uses a thermal activated structure (TABS) as the main part of the HVAC system [15]. The comfort evaluation and the annual energy consumption of this system were also presented. Song et al. [16] considered an active pipe-embedded building envelope to be an energy-efficient HVAC system to reduce and shift the peak load of an HVAC system in a campus building in South Korea, and the optimized operation strategy is also presented.

Although active pipe-embedded building envelope has been used for many actual building envelopes in the world, the heat transfer model is barely mentioned, while the heat transfer model is very important to analyze the heat transfer thermal performance [7,25]. As the active pipe-embedded building envelope with the embedded pipe, the structure is complicated. The heat transfer model of this structure is difficult developed.

The heat transfer models of the pipe-embedded structure (such as pipe-embedded structure for snow melting system, pipe-embedded floors, and pipe-embedded ceiling etc.) for thermal performance prediction have been presented by many researchers. The pipe-embedded structure for snow melting system is the earliest application of the pipe-embedded structure, Schnurr and Rogers [17] proposed a two-dimensional steady-state heat transfer model of this structure, and finite difference method is employed to solve the temperature distribution for optimizing system design. The pipe-embedded structure for floors or ceilings began in 1980s. The earliest two-dimensional steady model of pipe-embedded structure as ceiling for hot water heating is proposed by Zhang and Pate [27]. Subsequently, the accompanying experiments were conducted to validate the accuracy of this model [28,29]. In the 1990s, a steady-state fin model for predicting the heat transfer performance of the pipe-embedded structure as floor/ceiling is presented by Kilkis et al. [8]. Subsequently Kilkis et al. [9] used a finite element package to validate the accuracy of this model.

In addition, some simplified models of this structure also have been presented. A simplified steady-state model of the active pipe-embedded structure for air-conditioning was presented by Koschenz and Dorer [10]. This simplified steady-state model is in fact a pure resistant model. This model was used for the design of an active pipe-embedded structure for a new exhibition building in Zurich, and can be used for simple hand calculation for rough system configuration. In 2005, a dynamic simplified RC-network model for pipe-embedded structure was proposed by Jóhannesson [20]. Dynamic simplified RC model (i.e., resistance and capacitance model) is the best candidate for thermal performance prediction since the dynamic thermal process in the structure can be predicted accurately by this model. This kind model also can be solved easily for convenient integration with energy simulation software.

Active pipe-embedded building envelope is similar to floors/ceiling in term of structure. However, the heat transfer of the active pipe-embedded building envelopes is affected additionally and significantly by the outdoor environment. Zhu et al. [26,30] presented the frequency-domain finite difference (FDFD) model of the active pipe-embedded building envelope for frequency response analysis of the active embedded-pipe building envelope under various disturbances. FDFD model can predict the frequency characteristics directly and quickly. However, this model is still a numerical model and hard to be integrated with conventional energy simulation software. Subsequently, Zhu et al. [31,32] proposed a dynamic simplified thermal model (RC model) of this structure. RC model can predict the frequency characteristics and can be integrated with conventional energy simulation software. However, the heat transfer along the pipe is not considered in this model.

This paper presents a semi-dynamic thermal model of active pipe-embedded building envelope including two parts. The first part is the simplified dynamic RC model, which is used to calculate the heat transfer along the width of this structure. The second part is a classical NTU model for calculating the heat transfer along the pipe and total heat transfer on both surfaces of this structure. Both parts are coupled together to determine the average temperature of the building envelope mass and the outlet water temperature of the active structure etc. A CFD model is developed to act as a virtual experimental test rig to simulate the thermal characteristics of this structure for validating the semi-dynamic model and for performance evaluation. The accuracy of the semi-dynamic model with different water flow and the accuracy of the semi-dynamic model of different active pipe-embedded building envelopes are also presented and analyzed.

2. Overview of the semi-dynamic simplified model

An active pipe-embedded building envelope can be coupled with low-grade energy sources to offer reductions in energy consumption, peak electrical demand and energy costs without lowering the desired level of comfort conditions [31]. A dynamic model of the active pipe-embedded building envelope is of important to be integrated in conventional energy simulation tools to evaluate the energy and environment performance when this structure is integrated in a building system and coupled with low-grade energy sources. Fig. 1 shows the overview for developing a semi-dynamic simplified model. To develop this semi-dynamic

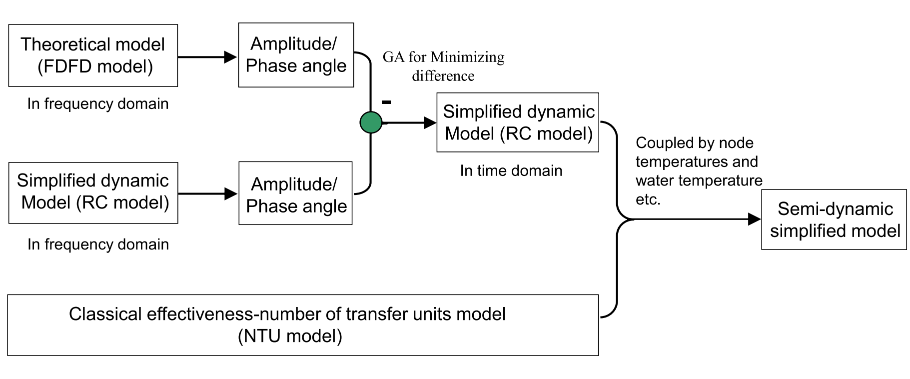

Fig. 1. Overview of the semi-dynamic simplified model.