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Experimental validation of a semi-dynamic simplified model of active pipe-embedded building envelope

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ABSTRACT

Active pipe-embedded building envelope can allow for substantial heat flow for relatively small temperature difference due to the embedded pipes in the external wall/roof. This structure can directly utilize the low-grade sources for reducing building cooling/heating load and improving indoor thermal comfort by intercepting the heat gain/loss through the building envelope due to the circular water inside the embedded pipe. This paper presents the experimental validation of a semi-dynamic simplified model of the active pipe embedded building envelope. The experiment test rig consists of two environment chambers with one for simulating the ambient environment and one for indoor environment with a pipe-embedded building envelope sample separating both chambers. A small chiller and a buffer tank are installed to provide stable water temperature for the test sample. The temperatures and heat fluxes on both sides of the test sample, the inlet and outlet water temperature as well as flow rate are measured. The measured boundary conditions are used as the inputs of the semi-dynamic simplified model for calculating the thermal performance of the active structure. The results show the semi-dynamic simplified model can predict the semi-steady or pure dynamic thermal performance of the pipe-embedded building envelope very well by comparing with the measurement.

1. Introduction

Active pipe-embedded building envelope is proposed recently [1,2]. This structure is a building envelope with pipe embedded in the external wall/roof and can utilize circulating water in the pipe to remove/release heat inside the structure directly. Active pipe-embedded building envelope is similar with pipe-embedded floors or ceilings for radiant heating/cooling. Pipe-embedded floors or ceilings allow substantial heat flows even for relatively small temperature difference between the mass and water and can utilize low-grade energy sources since the heat transfer surface between the slab mass and water is very large [3–5]. Active pipe-embedded building envelope also has this advantage. In addition, another advantage of this structure is that it can intercept the heat/cold permeation through the external wall from outdoor environment to indoor space. As a result, the indoor cooling load or heating load is reduced by directly using the low-grade energy without involving any mechanical cooling/heating equipment. Of course, the active pipe-embedded building envelope is the same as the pipe-embedded floors or ceilings for radiant heating/cooling when the wall is highly insulated from outdoor environment. Usually, groundwater, the cooling water produced by cooling towers, and geothermal energy produced by the ground-coupled heat exchanger system etc. can be used as the low-grade energy sources [6–8]. These low-grade energy sources are almost free and energy is only consumed by the circulating water pump.

The heat transfer model of the building envelope are essentially needed for estimating the cooling or heating energy consumption for performance monitoring, diagnosis and control strategy analysis [9–14]. Active pipe-embedded building envelope is different from the traditional building envelope due to the pipe-embedded layer. The material of the pipe embedded layer may be concrete or plaster. Due to the pipe-embedded layer and embedded pipes, the heat transfer of the active pipe-embedded building envelopes becomes complicated, and the model for heat flow calculation is not easy to develop. The heat transfer model of active pipe-

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embedded building envelope is rarely mentioned although the models of pipe-embedded structures (such as pipe-embedded structure for snow melting system, pipe-embedded floors, and pipe-embedded ceiling) are presented by many researchers [15–21].

As far as simplified model for pipe-embedded floor/ceiling is concerned, Koschenz and Dorer [21] developed a simplified steady-state pure resistant model of the pipe-embedded ceiling for air-conditioning. Weber and Jóhannesson [22] presented a dynamic simplified RC-network model for the pipe-embedded floor/ceiling, and this model is validated by measurement in time domain [23]. Dynamic simplified model are preferable to predict the dynamic thermal process in the structure for thermal performance prediction, and can be integrated with conventional energy simulation software such as TRNSYS, EnergyPlus, and DeST etc. [24,25].

Active pipe-embedded building envelope is similar to the pipe-embedded floors/ceiling in terms of structure. For the heat transfer of the pipe-embedded floor/ceiling, it is only affected by the indoor environment disturbance and the circular water disturbance in the embedded pipe. The heat transfer problem can be easily simplified because the indoor environment disturbance does not change abruptly and even may be regarded as constant if the solar radiation is absent [26,27]. However, the heat transfer of the active pipe-embedded building envelope is affected additionally and significantly by the outdoor environment especially when the outside of the building envelope is not enclosed with a thick insulation-skin. The brick or concrete exterior wall without insulation outside is still widely used in rural regions and many urban buildings in China. The outdoor thermal disturbances such as solar radiation and air temperature etc. change much more abruptly than the indoor environment disturbance. In this case, the fore-mentioned heat transfer models of pipe-embedded floor/ceiling may not be effectively used for the pipe-embedded building envelope. Therefore, it's necessary to develop a more efficient and accurate heat transfer model of the pipe-embedded building envelope which may be subjected to abrupt thermal disturbances.

For the heat transfer analysis of the pipe-embedded building envelope, Zhu et al. [2] presented a two-dimensional numerical frequency-domain finite difference (FDFD) model for analyzing the frequency thermal response of this structure under various disturbances. The heat transfer along the pipe line was not considered in the FDFD model due to the assumption that the water temperature change along the pipe line is very small. This FDFD model was further validated by experimental measurements in time domain by Xie et al. [28]. Zhu et al. [29,30] developed a dynamic simplified thermal model (RC model) of this structure for evaluating the frequency thermal characteristic along the width direction (i.e., the heat transfer along the pipe length direction is neglected), and the model parameters are identified by using Genetic Algorithm to match its frequency thermal response with the theoretical thermal response predicted by the FDFD model. Furthermore, Zhu et al. [31] presented a semi-dynamic simplified model (i.e. the coupled RC model and NTU model) of this structure by considering the heat transfer (i.e. RC model) along the width direction of the wall and the heat transfer (i.e. NTU model) along the direction of the pipeline. This model is more preferable for practical engineering application since it can predict the heat transfer along the width direction of the wall (such as the surface temperature or heat flux) and the outlet water temperature and total heat transfer between the wall and circulating water. This model is numerically validated by CFD model [31].

Although highly insulation layer for building envelope for very low *R* value is not involved in the Ref. [31], the simplified heat transfer model of the pipe-embedded exterior wall developed in the Ref [31] is still applicable to exterior walls with external skin of low R-value such as with insulation layer. This wall can be modeled simply and directly by adding a resistant component (i.e., R) to the exterior node of the developed simplified RC-network model presented in the Ref. [31].

This study mainly reports the setup of experiment test rig and the experimental validation of the semi-dynamic simplified model of the active pipe-embedded building envelope. The measured boundary conditions are used as the inputs of the semi-dynamic simplified model for thermal performance prediction. The outlet water temperature and the surface heat flux etc. are used for comparison to validate the semi-dynamic simplified model including the prediction of semi-dynamic thermal performance and dynamic thermal performance. The paper is organized as follows. At the beginning, the semi-dynamic simplified model of the active pipe-embedded building envelope is roughly briefed. Then, the experimental setup is described. Finally, the semi-steady state of this experiment is analyzed and the experimental validation is presented.

2. Description of the semi-dynamic simplified model

Fig. 1(a) shows the structure of the pipe-embedded building envelope. This structure consists of a 15 mm internal mortar layer, a 120 mm brick layer, a pipe-embedded mortar layer, a 120 mm brick layer, and a 15 mm external mortar layer in sequence. Polybutylene tubes with the diameter of 20 mm is used since polybutylene is economic, durable, and allow heat to pass through efficiently. The unit section *abcd* (which is the typical cross section of this structure) is used for model development. The heat transfer resistance due to the pipe width is very small when compared with the resistance of the brick layer or mortar layer. Therefore the thickness of pipe is neglected for investigating the thermal performance of the active pipe-embedded building envelope conveniently. Usually, the pipe-embedded building envelope may have different pipe spacings such as 100 mm, 150 mm, 200 mm, 250 mm and 300 mm etc. in practical applications. In this study, the pipe spacing is taken as 200 mm.

The semi-dynamic simplified model is a coupled model which is composed of a RC model (i.e., 5R2C model) and a *NTU* model, as shown in Fig. 1. The RC model is a simplified thermal-network model for predicting the dynamic heat transfer within the cross section *abcd* (see Fig. 1(a)), i.e., the heat transfer within *xoy* plane, based on the simplification that the heat transfer along the pipe length direction is neglected. *NTU* or *NTU*-ε model (i.e., effectiveness-number of transfer units) is a well-known method for solving heat transfer problems for sensible heat exchanger [32]. The *NTU* model can offset the disadvantage of the RC model, and it is used to predict the heat transfer along the pipe length direction, i.e., the *z* direction as shown in Fig. 1(a).

As shown in Fig. 1(b), the RC model is a dynamic second-order simplified thermal-network model. Only two capacity nodes (i.e., C_1 and C_2) are used to represent the capacity of the whole pipe-embedded structure, which will decrease the computation time to a large degree. R_1, R_2, R_3, R_4 and R_5 are the thermal resistance components between two adjacent temperature nodes. In this model, T_{out} is the outdoor air temperature, T_{in} is the indoor air temperature, and T_w is the average temperature of the water. T_1 and T_2 are the inside node temperatures of the RC model. The parameters of the RC model are determined by using a GA-based parameter identification by matching its frequency thermal responses with the theoretical frequency thermal responses predicted by the Frequency Domain Finite Difference (FDFD) model. The detailed description about the identification procedure can be found in Ref. [30]. *NTU* model is shown in Fig. 1(b). *K* is the overall heat transfer coefficient, *L* is the total length of the pipe, *NTU* is the