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Experimental validation of frequency-domain finite-difference model of active pipe-embedded building envelope in time domain by using Fourier series analysis

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ABSTRACT

Active pipe-embedded building envelope is a new kind of external building wall or roof which usually has pipes embedded in it to let water circulate in these pipes for heat transfer. This structure may effectively intercept the heat/coolth from the ambient environment to indoor space and provide extra space conditioning for the indoor space. Frequency-domain finite-difference (FDFD) model can predict the frequency thermal response of active pipe-embedded building envelope directly and provide some important guidelines for system control and system sizing. This paper presents the experimental validation of this model in time domain by using Fourier series analysis. An experiment test rig was developed for the thermal response measurements of the pipe-embedded building envelope under pre-defined conditions. First, the measured time series of surface temperatures are transformed into complex Fourier series by using Discrete Fourier Transform and applied into the FDFD model as the boundary condition for calculation. Then, the calculated frequency thermal responses by FDFD model can be easily transformed into time series by using Inverse Discrete Fourier Transform. Finally, the time-domain thermal responses of FDFD model are obtained. The results show that the calculated time-domain thermal responses of the active pipe-embedded building envelope by using FDFD model agree well with the experimental measurements.

1. Introduction

Active pipe-embedded building envelope (i.e. wall or roof) is a new kind of building envelope which has pipe embedded inside and lets the circulating cool water or hot water pass through it to temper the building envelope. It not only can intercept the heat/coolth exchange between the ambient environment and the indoor space to reduce building cooling/heating load but also provide extra space conditioning for the room [1]. The circulating water in the pipe-embedded building envelope functions as a heat sink or heat source to discharge or charge the pipe-embedded building envelope actively, distinguished from passive application forms (e.g. a high-mass solid building envelope [2,3]). Passive applications utilize the thermal storage of building mass to shift or reduce the peak cooling or heating load in the forms of passive heat exchange. Just like the other pipe-embedded structures such as pipe-embedded floor or ceiling etc., the pipe-embedded building envelope has some similar advantages over the traditional air-conditioning system such as more stable and comfortable inner environment, no drought sensation, utilization of relatively low (high) temperature water produced by renewable energy [4–7]. The purpose of the research project about the active pipe-embedded building envelope is to investigate the insulation effect and the space cooling capacity of this structure as well as the feasibility of integrating this structure with the low-grade or renewable energy resources. For this purpose, both the efficient and accurate heat transfer model of this structure and relevant experiments are necessary.

Since the transient heat transfer of this structure with high thermal inertia is complicated especially with heat/coolth storage process, accurate heat transfer model of this structure is important for system size and optimal system operation. There are large amount of researches aimed at the heat transfer model of the pipe-embedded structure such as pipe-embedded floor or ceiling while the heat transfer model of the pipe-embedded building envelope is rarely mentioned.

Analytical solution is one of the most chosen ones for the heat transfer problem. Different from panel structure, the geometrical

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Nomenclature

c	specific heat (J/(m^2 K))
λ	thermal conductivity (W/m K)
ρ	density (kg/m^3)
θ	temperature (K)
A	amplitude of the harmonic temperature variation (K)
S_p	spacing between adjacent pipes (mm)
δ	thickness of the pipe-embedded building envelope (mm)
N_c	the total number of the cells of FDFD model
s	heat transfer coefficient between two contiguous nodes (W/m K)
x	space coordinate (m)
y	space coordinate (m)
dx	y-direction increment (m)
dy	x-direction increment (m)
i	symbol of $\sqrt{-1}$
ω	angular frequency (rad/s)
φ	phase angle (rad/s)
u	real part of the complex quantity
v	image part of the complex quantity
d_n	discrete Fourier series of periodic time series
$f(t)$	periodic continuous-time signal
t	time (s)
Δt	sampling interval (h)
N	total number of the discrete values in a time series
h	number of harmonics
S_h	total energy of h harmonics
ζ_h	percentage proportion of S_h and $S_{N/2}$
P_k	time-domain thermal responses at the kth time step
$\bar{P}$	steady-state time-domain thermal responses
$\tilde{P}_{(n,k)}$	dynamic time-domain thermal responses the nth harmonic at the kth time step
$\theta'_j(k \cdot \Delta t)$	time-domain temperature response of cell j at kth time step (K)
$\bar{\theta}'_j$	time-domain steady-state temperature response of cell j (K)
$\tilde{\theta}'_j{}^{(n,k \cdot \Delta \tau)}$	dynamic time-domain temperature response (i.e. temperature responses to the harmonic with ω>0) of cell j to the nth harmonic at the kth time step (K)
$u'_{(n,j)}$	the real part of the frequency temperature responses of cell j to the nth harmonic calculated by FDFD model
$v'_{(n,j)}$	the imaginary part of the frequency temperature responses of cell j to the nth harmonic calculated by FDFD model
DFT	discrete Fourier transform
IDFT	inverse discrete Fourier transform
FDFD	frequency-domain finite-difference

Symbols

~	dynamic response
–	steady/average response
ˆ	conjugate complex number
í	the thermal responses calculated by FDFD model

shape of the pipe-embedded structures (i.e. pipe-embedded floor or ceiling) are irregular, and the heat transfer problem of this structure is difficult to solve analytically and a large degree of model simplification must be made for analytical solution [8–11]. Numerical method such as finite difference method (FDM), finite element method (FEM), finite volume method (FVM) etc. can provide accurate solutions for the heat transfer problem of the pipe-embedded structure as long as the meshing is sufficiently denser. Many researchers [12–17] developed detailed numerical models for the pipe-embedded radiant ceiling panel or hydronic heating floor, and some experiments were carried out to validate the numerical model. These numerical models are calculated in time domain. The computation cost is heavy, and the calculating process is also time-consuming especially for obtaining the quasi-steady-state solution of the periodic heat transfer problem because the repetitive iteration process for stabilization is required.

Pipe-embedded floor or ceiling is generally imposed by two thermal disturbances i.e. circulating water in pipes and indoor environment. However, active pipe-embedded building envelope (i.e. wall or roof) is imposed by the violently changed ambient environment except circulating water in pipes and indoor environment. The heat transfer problem of active pipe-embedded building envelope becomes more complicated than that of the pipe-embedded ceiling/floor. The ambient environment including outdoor air temperature, solar radiation etc. change rapidly in a day. The fore-mentioned steady-state analytical solution of pipe-embedded structures such as pipe-embedded floor or ceiling is not applicable to the pipe-embedded building envelope. In fact, the analytical solution is very difficult to obtain. The numerical model in time domain is also time-consuming.

Frequency-domain finite difference (FDFD) method [18,19], a numerical method in frequency domain, has been widely used in the electromagnetic fields and shown its clear advantage over the time-domain numerical method in solving the periodic problem in this field or calculating the frequency characteristics of the magnetic field. Xie et al. [20] developed a FDFD model of pipe-embedded building envelope and calculated the frequency thermal characteristics of this structure by using this FDFD model. This FDFD model can give a fast and direct solution of the dynamic thermal characteristics of the pipe-embedded building envelope, and a thorough frequency thermal analysis of this structure can be easily achieved. Zhu et al. [21] used the FDFD model to calculate the theoretical frequency thermal characteristics of this structure as reference to develop an equivalent simplified RC-network model.

This paper presents the experimental validation of the FDFD model of the pipe-embedded building envelope in time domain since all the measurements are discrete time series and the validation in time domain is intuitional. An experiment test rig is developed for the measurements of the thermal responses of the pipe-embedded building envelope under pre-defined dynamic conditions. Since the required boundary conditions and the calculated results of the FDFD model are all in frequency-domain, Fourier series analysis methods including discrete Fourier transform (DFT) and inverse discrete Fourier transform (IDFT) [22] are used to realize the transformation of boundary conditions and calculated results between time-domain and frequency-domain results. The results show the FDFD model can predict the thermal performance with good accuracy, and is effective for thermal performance analysis.

2. Description of the frequency-domain finite-difference model

This model has been presented in Refs. [20,21]. It is duplicated here for coherence. Fig. 1 shows the typical cross section of the active pipe-embedded building envelope. Fig. 2 shows the typical operations of the active pipe-embedded building envelope. In cooling condition, the internal and external surface temperatures of this structure are lower than the corresponding indoor and outdoor environment temperature, respectively. The water pipe with