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Impact factors analysis on the thermal performance of hollow block wall

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ABSTRACT

In this paper, the influence on the thermal performance of hollow block wall produced by boundary condition, the thermo-physical properties of block materials, and the configuration of hollow block was analyzed, the regulations were obtained, and the optimization measures were proposed. For the analysis, the experiment and calculation were combined, and the thermal resistance, decrement factor, and time lag were considered as the evaluation indexes. The experimental method is herein called *temperature-change hot chamber method (TCHCM)*. The two-dimensional energy equation was discretized by *finite difference method (FDM)* with Gause–Seidel scheme, the *point iteration method (PIM)* was used, and the calculation program was developed in MATLAB environment. It was concluded that the thermal performance of wall is perfect with the thermal conductivity of block material lower than $1.0\,W\,m^{-1}\,K^{-1}$. Furthermore, when the thermal conductivity and the thermal capacity of block material are higher than $1.0\,W\,m^{-1}\,K^{-1}$ and $1.0\,MJ\,m^{-3}\,K^{-1}$, respectively, it is more effective to increase the thermal capacity than to decrease the thermal conductivity for the thermal performance improvement of wall. In addition, the main factors influencing thermal performance are ranked with the functions in descending order as: decreasing the thermal conductivity of block material, increasing the thermal capacity of block material, decreasing the equivalent thermal conductivity of the material inside holes, increasing block thickness (accompanying the increase of hole spacing), and increasing hole rows (maintaining small hole thickness).

1. Introduction

Building envelope can accumulate heat and consequently reduce the operating cost of building devices. The thermal performance improvement of building envelope, importantly influencing the building energy efficiency, becomes one of the key points of building energy-saving work. Energy-saving hollow block can reduce structural weight and improve the thermal insulation properties of wall due to the high thermal resistance of the relatively stagnant air inside block; consequently, the cooling load and energy consumption are reduced. Therefore, using the wall outfitted with energy-saving hollow block becomes one of the general methods to improve the thermal performance of building envelope.

Hollow block is non-homogeneous component. Therefore, the heat transfer within hollow block can not be simplified as one-dimensional process; otherwise, large error will probably happen [1]. Most researchers calculate and analyze the hollow block wall using two-dimensional or three-dimensional mathematical models. Lorente analyzed the thermal resistance of the hollow bricks of different structures using two-dimensional model. He concluded that the thermal resistance of wall reduced greatly when the hole rows were decreased and meanwhile the hole thickness was increased; increasing the height of brick is more effective for the improvement of thermal resistance than increasing the thickness [2]. Antoniadis, using Comsol Multiphysics software [3] and two-dimensional model with finite element method (FEM), analyzed the influence on the equivalent thermal conductivity of hollow brick produced by the factors such as the material type, structure of brick, hole rate, and the optimization measures were proposed [4]. Morales performed the optimization analysis on the equivalent thermal conductivity of the hollow clay bricks with different hole patterns using FEM. It was concluded that the holes being arranged in a quincunx, increasing the hole rows, avoiding

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Nomenclature

ρ	density of PCM (kg m^{-3})
λ	thermal conductivity (W m^{-1} K^{-1})
τ	time (s)
y	direction of width (mm)
T_{init}	initial temperature (°C)
h_a	the convective heat transfer coefficient when $x = 1$ (W m^{-2} K^{-1})
h_b	the convective heat transfer coefficient when $x = N_x$ (W m^{-2} K^{-1})
$f(\tau)$	heat flow function as a function of τ (W m^{-2})
$T_{x,y,\tau+1}$	the temperature of the point (x, y) at the time of $\tau + 1$ (°C)
σ'	maximum absolute error (°C)
i	sequence number of data
$N_{sta,i}$	i_{th} standard datum
λ_2	equivalent thermal conductivity of the material inside holes (W m^{-1} K^{-1})
c	sensible heat of PCM (kJ kg^{-1} K^{-1})
T	temperature (°C)
x	direction of thickness (mm)
$T(x, y, \tau)$	the temperature of the point (x, y) at time point τ (°C)
N_x	the total number of the meshes on the x direction
T_{fa}	the boundary air temperature when $x = 1$ (°C)
T_{fb}	the boundary air temperature when $x = N_x$ (°C)
$T_{x,y,\tau}$	the temperature of the point (x, y) at the time of τ (°C)
σ	standard error (°C)
n	amount of data
N_i	i_{th} datum
λ_1	thermal conductivity of block material (W m^{-1} K^{-1})

Subscripts

p	the boundary meshes when $x = 1$
E	the point right to the point p
S	the point under the point p
N'	the point above the point p'
$init$	initial
p'	the boundary meshes when $x = N_x$
N	the point above the point p
W'	the point left to the point p'
S'	the point under the point p'
sta	standard

thermal bridges, and the non-rectangular geometric holes contained within rectangles with a minimum thickness of 10 mm can provide greater thermal performance [5,6]. Li, combined TDMA (Tri-diagonal Matrix) method and Alternating Direction Implicit (ADI) method, studied the heat transfer processes of various hollow blocks of different structures. It was concluded that the heat radiation inside the holes increases the equivalent thermal conductivity of block; furthermore, the amount and arrangement of holes played important roles on equivalent thermal conductivity; however, the variation of the indoor and outdoor air temperature ranges had little effect on equivalent thermal conductivity [7,8]. del Coz Diaz, taking the overall heat transfer coefficient as the index, using response surface methodology (RSM) and finite element method (FEM), analyzed different types of hollow bricks. It was concluded that when the width of the recesses is equal to 10 mm and 30 mm, respectively, the increase and the decrease of the width give place to the decrease of the brick thermal conductivity; furthermore, an increase in length of the recesses and a decrease of the recesses' surface radiation emissivity imply a better thermal behavior [9,10]. Currently, most studies have been conducted aiming at reducing the equivalent thermal conductivity of hollow blocks [11–17]. In fact, the actual condition for the use of hollow block is dynamically varied. Wall's thermal resistance can be increased by reducing equivalent thermal conductivity; but this is often accompanied with the decrease of thermal capacity, which apparently weakens the ability against the fluctuation of temperature and heat flux. Therefore, only aiming at reducing the equivalent thermal conductivity of wall is one sided. The indexes such as thermal resistance, decrement factor, and time lag should be considered synthetically. As a result, researchers started to do the evaluations adding the indexes of decrement factor and time lag in recent years. Some of them analyzed the impact factors of decrement factor and time lag using one-dimensional heat transfer models [18–27]. In addition, Sala, using calibrated hot-box unit and FEM tested and calculated the response factors of hollow block wall [1]. Arendt proposed an optimized hole pattern and studied the effect of hollow ratio on the thermal parameters of hollow brick using two-dimensional energy equation. He presented the optimum hole rate under this hole pattern was 45–65%. The indexes used in the evaluation were time lag, decrement factor, equivalent thermal diffusivity and equivalent thermal conductivity [28]. Most researchers have only analyzed a certain class of impact factors influencing the thermal performance of hollow block, synthetic analysis with multiple factors has rarely been reported by which more innovative regulations can probably be gained. Furthermore, with different varieties of hollow blocks, the structural design generally depends on designer's experience, which leads to unreasonable use of materials and hole patterns. Hence, analyzing the impact factors on the thermal performance of hollow block wall systematically, and optimizing the hole pattern of block effectively become a necessary and urgent step for improving wall's energy-saving level, which can also provide principles for the related designing standards.

a) Structure of the hollow block (mm) b) Hollow block wall

Fig. 1. Hollow block and experimental wall.

In this paper, the influence on the thermal performance of hollow block wall produced by boundary condition, the thermo-physical properties of block materials, and the configuration of hollow block was analyzed, the regulations were obtained, and the optimization measures were proposed. The used indexes are thermal resistance, decrement factor, and time lag.

2. Mathematical model

2.1. Assumptions

In order to simplify the heat transfer model, the following assumptions are made: (1) all the materials are considered to be thermally homogeneous and isotropic media; (2) the thermal properties of each material are unchangeable during heat transfer process; (3) the equivalent thermal conductivity is applied for the air layers inside the block [29]; (4) according to the physical model (Fig. 1 and Fig. 5), the net heat flow on the vertical direction is zero,