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Numerical analysis on thermal performance of naturally ventilated roofs with different influencing parameters

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ABSTRACT

Ventilated roof can reduce the cooling load during summer period by decreasing transmitted heat flux of the building structures exposed to the solar radiation. In the present work, effect of different influencing parameters on thermal performance of naturally ventilated roofs on a residential building in Northeast China has been investigated numerically based on computational fluid dynamics (CFD), such as air gap thickness, roof slope, exhaust outlet size and absorption coefficient of external roof surface. The results show that the effect of ventilated layer on the temperature delay of roofs is strong, but the effect on the delay time is relatively weak. The air layer thickness, roof slope and exhaust outlet size also play an important role in the thermal performance of ventilated roof.

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1. Introduction

Energy and environment are the keys in the development of human beings. In the energy production from coal and fossil fuel, CO_2 is also produced and exhausted into the atmosphere, which is widely believed to be contributing to global warming (Erdem, Young, & Saffa, 2014). As one of the leading sectors of the energy consumption, about 40% of total fossil energy per each year in China was consumed in building sector (Zhou, Zhao, & Tian, 2012; Gao et al., 2014). Furthermore, the energy consumption of buildings is still increasing with the developing demand for the life style and the living standards, which will be estimated about 20×10^{12} MJ in 2020 in China (Sun, Zhang, Medina, & Lee, 2014). During recent years, researching the novel technology to improve energy efficiency and conservation in buildings has been one of the major issues of governments and societies, whose aim is reducing the energy consumption without affecting the thermal comfort level in a wide weather conditions.

Thermal loss of roof in the building envelope of a residential building is the main source, contributing approximately 70% of the total heat loss due to directly solar radiation and better location in the heat transfer between the exterior and the interior spaces of the building (Vijaykumar, Srinivasan, & Dhandapani, 2007; Chan & Chow, 2013; Al-Obaidi, Ismail, & Rahman, 2014). The common improvement in the thermal performance of roofs is enhancing the total thermal resistance of roofs by adding insulation ability, however it may not be rationally adopted in many practical cases because of roof thickness limitations or economic reasons. An alternative solution to improve the thermal performance is the reduction of heat flux through the roofs utilizing novel techniques, such as evaporative cooling technique roofs (Sahar & Yahyah, 2012; Artemisia, Dionysia, Theocharis, & Zacharopoulos, 2014; Haghighi, Golshaahi, & Abdinejad, 2015), green roofs (Pablo & Umberto, 2014), and ventilated roofs (Suresh, Srikanth, & Robert, 2011). Due to remarkable merits in reducing the solar heat gain and improving the indoor thermal comfort in summer, the naturally ventilated roof as a potential technology for minimizing energy consumption in the buildings is attracted more and more attention (Karam, Mazran, & Abdul, 2014).

When assessing the effectiveness of ventilated air layer for improving thermal performance of roofs, experimental methods are usually adopted to evaluate the energy reduction resulting from the use of ventilated air layer (Soubdhan, Feuillard, & Bade, 2005; Dimoudi, Lykoudisb, & Androutsopoulos, 2006a; Dimoudi, Androutsopoulos, & Lykoudis, 2006b; Kharrufa & Adil, 2008; D'Orazio, Perna, Principi, & Stazi, 2008; Lee, Park, Yeo, & Kim, 2009; Roels & Deurinck, 2011; Kośny, Biswas, Miller, & Kriner, 2012; Yew et al., 2013; Charde & Gupta, 2013). Most experimental studies of the ventilated roofs involved the measurement of surface temperature, airflow temperature and velocity, and heat flux transferred across roofs. For example, Lee et al. (2009) found that cavity ventilation, roof slope, intensity of solar radiation, the size and shape of the cavity, and panel profiles play an important role in the airflow and temperature distribution of the ventilation

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cavity. Kośny et al. (2012) experimentally found that about 30% heating and 50% cooling load reductions of the ventilation roof are possible.

Besides from the experimental researches, numerical modelling is also a powerful method to study ventilation applied in the roofs, which includes 1D (one-dimensional) (Sandberg & Moshfegh, 1998; Ciampi, Leccese, & Tuoni, 2005; Susanti, Homma, & Matsumoto, 2011; Chou, Chen, & Nguyen, 2013; Ahrab & Akbari, 2013; Kolokotroni, Gowreesunker, & Giridharan, 2013; Tong et al., 2014), 2D (two-dimensional) (Cěrne & Medved, 2007; Biwole, Woloszyn, & Pompeo, 2008; Gagliano, Patania, Nocera, Ferlito, & Galesi, 2012; DeBlois, Bilec, & Schaefer, 2013a,b; Piller, Polidoro, & Stalio, 2014; Tong & Li, 2014; Zingre et al., 2015), and 3D (three-dimensional) heat transfer models (Liberati, Spiga, & Zappavign, 2009; Seo et al., 2009; Norton, Grant, Fallon, & Sun, 2010). Theoretical studies based on 1D (one-dimensional) heat transfer model were conducted as well to analyse the thermal performance of naturally ventilated roofs. For example, Ciampi et al. (2005) investigated the convenience of using ventilated roofs for the reduction thermal loads in summer, and found that energy saving 30% can be achieved compared to the same non-ventilated structure. Tong et al. (2014) developed 1D model to predict the transient temperature of roof and transmitted heat flux through the multilayer roofs based on an analytical Complex Fast Fourier Transform (CFFT) method. Tong et al. also found that the solar reflectivity of roof plays an important role in the daily heat gain in Singapore. However, a lot of simplified assumptions need to be usually adopted in the 1D heat transfer model, and the air flow in the ventilated cavity cannot be shown.

The 2D heat transfer model was often used to predict the airflow temperature and velocity in ventilated roofs. For example, Cěrne and Medved (2007) presented a transient 2D heat transfer model of low sloped roof with forced ventilated cavity using Fourier series method. Biwole et al. (2008) investigated 2D heat transfer of the double-skin roofs with radiation, convection and conduction based on finite elements method. Gagliano et al. (2012) investigated thermal behaviour of ventilated roofs using the Fluent software, and found that the ventilated roofs can significantly reduce the heat fluxes up to 50% during summer season. DeBlois et al. (2013a) developed a 2D CFD model of the air gap with small expanded domains at the entrance and exit based on Fluent. Piller et al. (2014) presented analytical solutions to simulate numerically the 2D natural convection channel flow based on the Boussinesq approximation and neglecting viscous energy dissipation. Tong and Li (2014) developed a theoretical model to predict the heat flux transferred through the naturally ventilated roof due to coupled radiation and convection in roof cavity using the circuit transformation theory and CFD analysis. However, in the 2D heat transfer model, the effect of ventilated layer shape that is three-dimensional detailed construction of air layer in ventilated roof, and inlet or exhaust outlet on flow characteristic of the ventilated roof cannot be given, because the 2D heat transfer model cannot display the detailed configuration of inlet and outlet.

In general, 3D heat transfer model techniques provide more accurate predictions for the rates of induced airflow and convective heat transfer in the ventilated roofs, however they often require heavy computing resources. For example, Liberati et al. (2009) investigated a 3D profile of the air temperature in the duct to optimize the performance of roofing components equipped with a ventilated ∈ by means of a theoretical model and experimental tests. Seo et al. (2009) analysed airflow, internal air temperature distribution and ventilation efficiency of a conventional ventilation system using Fluent. Norton et al. (2010) developed predictive models of the indoor environment of a naturally ventilated livestock building based on response surface methodology and CFD code STAR-CCM+. Raya, Gong, Glicksman and Paradiso (2014) used a naturally ventilated atrium to validate three CFD turbulence models, RNG k–ε, k–ε and LES.

In the present work, a 3D heat transfer model was developed to predict the heat transfers of a naturally ventilated roof using CFD simulation, and the thermal behaviour of different ventilated roofs in Northeast cold area of China have been investigated numerically. This study also explored the influencing factors on the heat flux transferred into building interior, such as ventilated air gap thickness, roof slope, exhaust outlet size and absorption coefficients of external roof surface.

2. Physical and mathematical models

2.1. Model description

The modelling ventilated roof of a single residential building is located in Daqing city (a Northeast city in China), whose longitude and latitude are, respectively, 125.03° and 46.58°, which represents a typical cold area climate. The maximum and minimum historical average temperatures in summer are, respectively, 303 and 296 K, and the yearly total solar radiation intensity is 491.4 kJ/cm^2.

Fig. 1 shows the construction details of the modelling ventilated roof. In this modelling work, the length and width of the roof are 3 and 3 m. The ventilated roof is divided into four layers from top to bottom, which is, respectively, named as the first layer, the second layer, the third layer and the fourth layer. The first layer made of aluminium alloy plate is protective layer. The second layer is ventilated air layer. The third layer is the fine aggregate concrete layer, whose material is fine stone concrete. The fourth layer consisted of reinforced concrete is the base layer. The thermophysical properties of materials are shown in Table 1, in which ρ, k, c_p are the density, thermal conductivity and specific heat, respectively. μ and β are dynamic viscosity and coefficient of expansion of air, respectively. In the ventilated air layer, the two rectangular faces represent the two inlets and the one horizontal face on the top is the exhaust outlet, as shown in Fig. 1. In order to analyse the impact of the exhaust outlet size on the thermal performance of ventilation roof, a variable β that is defined as the area ratio of the exhaust outlet and inlet.

2.2. Governing equations and boundary conditions

Assumptions for the mathematical model have been listed as follows: (1) The dynamics of airflow in ventilated air layer are fast compared to building temperature dynamics, and supposed the airflow in the cavity reaches the stage of turbulent. (2) The channel of ventilated air layer is smooth. (3) The density of air is a function of temperature only, and air does not participate in radiative heat transfer, and all other material properties are independent

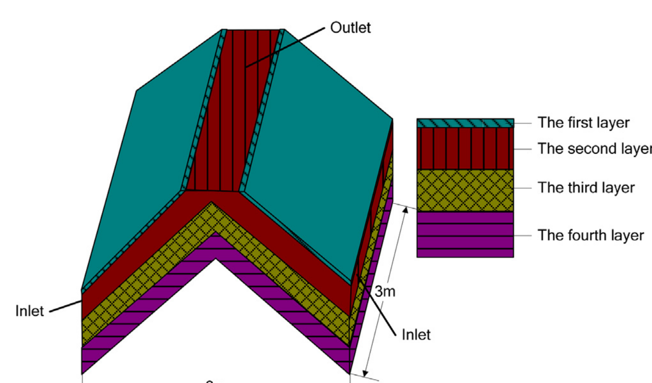

Fig. 1. Construction of roof (Left: skeptical construction; Right: construction details).

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