Building and Environment 81 (2014) 296–308

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

An efficient model development and experimental study for the heat transfer in naturally ventilated inclined roofs

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ARTICLE INFO

Article history:
Received 30 April 2014
Received in revised form
7 July 2014
Accepted 10 July 2014
Available online 21 July 2014

Keywords:
Roof heat gain
Natural ventilation
Thermal resistance circuit
Heat transfer modeling

ABSTRACT

Roof ventilation is an efficient way to reduce the heat transmission into building interior in summer. In this work, a theoretical model is developed to predict the heat flux transferred through the naturally ventilated inclined roof in a fast and accurate manner. In particular, the thermal resistance due to the coupled radiation and convection in roof cavity is modeled using the circuit transformation theory. Moreover, based on the computational fluid dynamics (CFD) analysis, correlations are proposed for the convective resistances in the naturally ventilated inclined cavity. Laboratory experiments are further carried out to validate the CFD model, and a satisfactory agreement is found between the experimentally measured and numerically simulated airflow velocity and temperature in the cavity. In order to evaluate the accuracy of developed model, the heat flux transferred into building interior is predicted by both the developed model and a full CFD model. A good agreement is achieved between the predictions of the two models. Based on the developed model, parametric studies are conducted to investigate the influences of key roof parameters on the heat flux transferred into building interior. Ranked in order of significance, the influential parameters are the solar reflectance of exterior roof surface, infrared emittance of cavity surface, thermal resistance of lower roof slab, thermal resistance of upper roof slab, roof inclination and cavity spacing.

1. Introduction

In recent years, the naturally ventilated roofs were widely studied due to their remarkable merits in reducing the solar heat gain and improving the indoor thermal comfort in summer. A common ventilated roof consists of two parallel solid slabs and a delimited open-ended air cavity between the two slabs. An upward flow is formed inside the roof cavity due to buoyancy force, which contributes to carrying out part of the accumulated heat accumulated in the roof and cut down the heat transmission into building interior.

A literature review reveals that many experimental and theoretical studies have been carried out to evaluate the thermal behavior of naturally ventilated roofs. Most experimental studies on the ventilated roofs involved the measurements of roof surface temperature, airflow temperature and velocity, or heat flux transferred across the upper and lower roof slabs. For example, Dimoudi et al. [1] performed a field experiment on a full-scale roof in the summer of Greece in 2006. They examined the effects of roof ventilation and radiant barrier on the roof heat gain. It was found that the application of a 6-cm ventilated cavity reduced the roof heat gain by 56% during the daytime compared with an unventilated roof. The radiant barrier with the low infrared emittance effectively reduced the radiative heat transfer from upper to lower cavity surface, and thus increased the daily heat gain reduction of ventilated roof to 68%. In 2007, Puangsombut et al. [2] carried out experiments on a ventilated roof with uniform heat flux on the upper cavity surface. They examined the airflow rate and convective heat transfer in the inclined roof cavity using two dimensionless parameters: Nusselt and Reynolds numbers. Based on measured data, these two parameters were correlated to three variables: Rayleigh number, roof inclination and aspect ratio. After the application of radiant barrier, it was found that the heat flux transferred through the lower slab reduced by about 50%, and the convective heat transfer and airflow rate in the roof cavity increased by about 40–50%. Lai et al. [3] carried out experiments on a scaled ventilated inclined roof with the upper roof slab heated by a lighting system. They measured the airflow velocity and temperature in the cavity for different roof inclinations and spacings. A correlation was proposed for the Nusselt number in the ventilated

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http://dx.doi.org/10.1016/j.buildenv.2014.07.009
0360-1323/

cavity, and an optimum cavity spacing of 10 cm was suggested for the 1-m long roof for the maximum convective heat transfer. In 2008, Chang et al. [4] carried out experiments on an asymmetrically heated ventilated roof for different inclinations and cavity spacings. Based on measured data, they calculated the U-values of ventilated roofs and correlated U-values to the Rayleigh number, roof inclination and cavity aspect ratio. In 2009, Susanti et al. [5] carried out experiments on a 4.8-m long naturally ventilated inclined roof under different heating intensities, and measured the induced airflow velocity and temperature in the cavity with different opening ratios. Moreover, the induced airflow velocity and temperature rise were correlated to the incident heat flux, cavity spacing, roof inclination and opening ratio. In 2011, Roels and Deurinck [6] evaluated the effect of radiant barrier on the thermal performance of ventilated roofs using three methods: laboratory experiments, field testing and numerical modeling. The laboratory experiment and simulation showed that the radiant barrier reduced the daily heat gain of roof effectively, while the field testing revealed that the air-tightness, wind and stack effects were important and could disturb the potential benefits of using a radiant barrier.

Theoretical studies were conducted as well to analyze the thermal performance of naturally ventilated inclined roofs. The computational fluid dynamic (CFD) technique was often used to predict the induced airflow temperature and velocity in ventilated roofs. For example, Biwole et al. [7] numerically modeled the radiative, convective and conductive heat transfers through a ventilated roof, and validated the numerical model using field experiments on a ventilated roof that was formed by adding a metallic screen on a metal roof. They simulated the impacts of various parameters on the energy efficiency of ventilated roofs, including the infrared emittance of sheet metal, solar reflectance of screen, insulation thickness and roof inclination. In 2010, Chami and Zoughaib [8] developed a CFD model to simulate the convective heat transfer in the roof cavity, and validated the model through measurements on a scaled roof using the particle image velocimetry system. Moreover, correlations were proposed for the induced airflow rate and convective heat transfer coefficient in the cavity. More recently, Gagliano et al. [9] analyzed the impacts of roof ventilation and thermal resistances of roof slabs on the heat flux transferred into building interior using the CFD code Fluent. It was revealed that roof ventilation can reduce almost 50% of transferred heat flux in summer, and the optimum position for the thermal insulation layer is under the air layer adhering to the lower slab. Miller et al. [10] proposed a correlation for the laminar airflow rate in the inclined cavity through CFD analysis, and developed an algorithm to predict the convective heat transfer coefficient in the cavity heated from above or below. In addition to ventilated roofs, CFD technique was used to analyze the laminar [11], transitional [12,13] and turbulent [14,15] flow in the naturally ventilated inclined channels or photovoltaic panels as well. In general, CFD techniques provide accurate predictions for the rates of induced airflow and convective heat transfer in the naturally ventilated cavities, whereas they often require heavy computing resources. In order to provide a fast estimation, Ciampi et al. [16] developed an analytical model to analyze the energy savings of ventilated facades using the thermal circuit analysis and Gnielinski correlation [17]. This model was later applied to the energy analysis of ventilated roofs [18]. However, the Gnielinski correlation was developed for the turbulent forced convection in tubes or pipes with circular sections, and it expresses the Nusselt number as a function of the Reynolds number and Darcy friction factor [17]. While the roof cavities are mostly rectangular and the Reynolds number is often unknown for the natural convection flow, it might be inappropriate to use the Gnielinski correlation to estimate the natural convective heat transfer in the roof cavity.

Nevertheless, the fast and accurate determination of the heat flux transferred through the naturally ventilated inclined roof is a great challenge. As shown in Fig. 1, the heat transfers through a ventilated roof are quite complex, including the coupled convective and radiative heat transfers at the exterior and interior roof surfaces (q_o and q_i), the conductive heat transfers within the upper and lower roof slabs ($q_{cond,\,u}$ and $q_{cond,\,l}$), the convective heat transfers at the upper and lower surfaces of cavity ($q_{conv,\,h}$ and $q_{conv,\,c}$), and the radiative heat transfer from upper to lower surface of cavity (q_{rad}). Among these heat transfers, q_o and q_i are affected by the thermal resistances of exterior and interior air films, $q_{cond,\,u}$ and $q_{cond,\,l}$ are affected by the thermal resistances of roof slabs, and q_{rad} is readily predictable using the radiation theory [19]. However, $q_{conv,\,h}$ and $q_{conv,\,c}$ are difficult to evaluate and affected by various factors, such as cavity aspect ratio, roof inclination, outdoor air temperature, and surface temperatures of cavity walls. The surface temperatures of cavity walls are further affected by the other conductive, radiative and convective heat transfers. Therefore, all these heat transfers should be considered simultaneously to provide an accurate prediction for the heat flux transferred into building interior q_i.

In present work, a novel model is developed to predict the heat transfers through a naturally ventilated roof using the circuit transform theory and correlations proposed from CFD simulation. Compared with the existing models, the developed model combines the advantages of analytical approach and numerical simulation, and it is capable of predicting the heat flux transferred into building interior q_i with high effectiveness and accuracy. In addition, the convective heat fluxes $q_{conv,\,h}$ and $q_{conv,\,c}$ are estimated using the correlations which are firstly proposed from the CFD analysis of the turbulent flow in naturally ventilated inclined cavities.

2. Model development

Considering a naturally ventilated roof as illustrated in Fig. 1, it is exposed to the solar irradiance E (W/m^2), outdoor air temperature T_o and indoor air temperature T_i. From top to bottom, the surface temperatures of the upper and lower roof slabs are denoted as T_1, T_2, T_3 and T_4 respectively. The thermal network for a ventilated roof is shown in Fig. 2(a), in which r_e and r_i are the thermal resistances of exterior and interior air films, r_a and r_b are the thermal resistances of upper and lower roof slabs, r_{rad} is the radiative resistance between the upper and lower cavity surface, r_H and r_C are the thermal resistances due to convection between

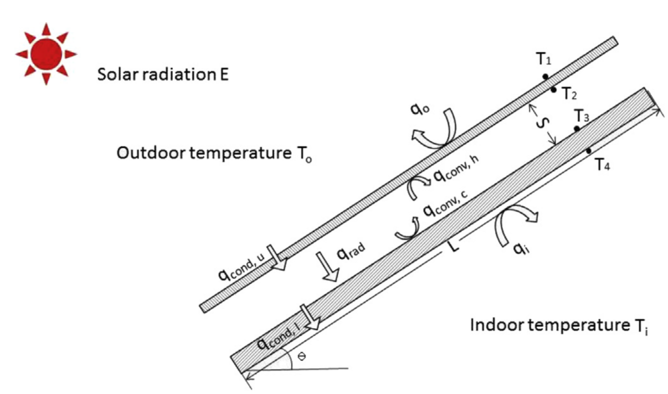

Fig. 1. Heat transfers across a ventilated roof.