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Experimental and numerical investigations of combined free convection and radiation heat transfer in an upward-facing cylindrical cavity

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A B S T R A C T

Due to the emergence of second-stage concentrators and lens systems, heat transfer in upward-facing cavities becomes more and more important. In the first part of this paper, the impacts of heat flux, cavity tilt angle and surface heating condition on combined free convection and radiation heat transfer in an upward-facing cylindrical cavity subjected to constant heat flux were explored experimentally. Results suggest that the studied parameters seriously affect the free convection and radiation heat transfer in cavity. Compared with the monotonous variations of the cavity surfaces average temperature, as well as the free convection and radiation heat transfer Nusselt numbers Nu_c and Nu_r with cavity tilt angle for downward-facing cavity, there exist extremums for upward-facing cavity. In view of this interesting result, three-dimensional numerical analysis validated by related experimental results was performed to further investigate the effect of cavity tilt angle from the perspective of physical mechanism. Taking heat flux and cavity tilt angle as independent parameters, empirical correlations of Nu_c and Nu_r in three surface heating conditions were proposed separately. In addition, a novel correlation incorporating the effect of surface heating condition with considerable accuracy was firstly developed to facilitate the engineering application whose surface heating condition alters frequently.

1. Introduction

Combined free convection and radiation heat transfer in various cavities has received much attention for its wide engineering applications, such as the cooling of electronic equipments [1] and the cavities in solar thermal power systems. In these investigations, attention is mainly focused on the cavities operating in the sideward or downward positions, while the study about upward-facing cavities was limited. Recently, due to the emergence of second-stage concentrators and lens systems [2], especially, Fresnel lenses, which can efficiently utilize solar energy, the fields for application of upward-facing cavities were extended, such as solar thermoelectric generation systems [3] and surface modifications of metallic materials [4,5]. As a result, heat transfer in upward-facing cavities has become undeniably important, and the relevant studies were presented below. For clarity, the downward, sideward and upward facing positions as well as the definition of cavity tilt angle are shown in Fig. 1.

In 1983, Clausing et al. [6] performed experiments to investigate the heat transfer in an isothermal cubical cavity, based on that, an analytical model for estimating convection heat transfer was proposed. However, only two upward-facing cavity tilt angles were considered. After about ten years, Showole and Tarasuk [7] experimentally and numerically studied the steady two-dimensional laminar free convection heat transfer in an isothermal upward-facing open cavity, in which Mach–Zehnder interferometer was used. The flow and temperature characteristics inside the cavity were presented, and Nusselt number correlations considering the effects of cavity tilt angle and Rayleigh number were developed. The qualitative and quantitative analyses about convection heat transfer in isothermal spherical and hemispherical cavities with negative tilt angles were explored by Leibfried and Ortjohann [2]. Two models for calculating convection heat transfer were reported. Research revealed that, unlike gradually decreasing with a rise of cavity tilt angle from 0° to 90°, a maximum of free convection heat

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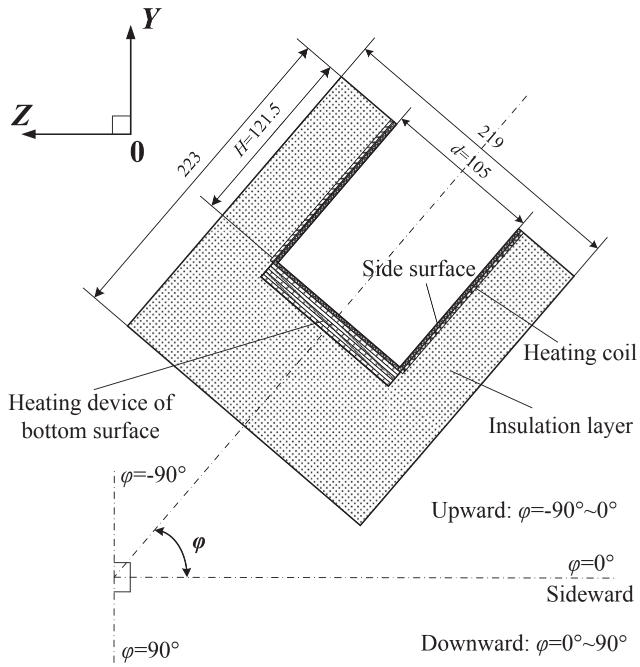

Fig. 1. Definition of cavity tilt angle and cross-section view of cavity in YOZ plane (unit: mm).

transfer existed as cavity tilt angle varied from −90° to 0°. A series of studies on free convection heat transfer in the upward-facing cavities (rectangular [1,8,9], semi-cylindrical [10]) with constant heat flux were performed experimentally by researchers from Kuwait University. The influences of aperture size and position [8], cavity tilt angle [1,8–10], surface heating condition [9] were considered. The results showed that the effect of cavity tilt angle on free convection was less obvious in upward-facing positions compared with those in downward-facing positions, and it can be strongly affected by surface heating condition. Also, some empirical correlations on free convection were proposed. Free convection and radiation heat transfer in a two-dimensional square upward-facing cavity with the opposite wall to the aperture holding a constant temperature of 500 K and the other walls keeping insulated were conducted by Hinojosa et al. [11], in which the influences of cavity tilt angle and Rayleigh number were considered. The results suggested that compared with radiation heat transfer, free convection varied substantially with cavity tilt angle, which was related to Rayleigh number. Using the numerical method, Bilgen and Oztop [12] investigated the free convection in inclined partially open square cavities, where the upward positions were included. A conclusion was drawn that the free convection heat transfer was not a linear function of cavity tilt angle. Moreover, in the investigations carried out by McDonald [13] and Taumoefolau et al. [14], the free convection heat transfer in upward-facing cavities were also mentioned briefly.

Latest, some upward-facing cavities having different geometries incorporated with a high concentration imaging point focus Fresnel solar collector were developed by Xie et al. [15,16], and their performances were discussed experimentally and numerically. In Ref. [15] the temperature distributions inside the cavities with or without ultra-white glass cover were presented. The results indicated that the heat transfer in the conditions without glass cover was more pronounced than that with glass cover, and the temperature distributions of the latter were more uniform.

A literature review shows that, the investigation on heat transfer in upward-facing cavities is immature and some defects are identified. Firstly, a conflict about the effect of cavity tilt angle in upward-facing cavities is raised. Refs. [2,11,14] show that the free convection heat transfer can be maximized at the cavity tilt angle between −90° and 0°, which does not agree with some results provided by Refs. [1,8–10]. Secondly, to the best knowledge of authors, the reason for maximizing free convection heat transfer is only analyzed qualitatively by Refs.[2,8], no quantitative analysis is performed up to now. Thirdly, most of these investigations are subjected to uniform surface temperature condition. However, non-uniform surface temperature conditions in practical applications are always encountered, where the temperature distribution inside the cavities and the heat transfer characteristics are not clear and need to be further investigated. Last but not least, radiation heat transfer has not been researched systematically in all above studies except Ref. [11]; nevertheless, the role of radiation heat transfer may be significant since both the flow and temperature fields in cavities can be affected by radiation [17]. Meanwhile, only Refs. [1,2,7–9] have proposed the empirical correlations for calculating free convection heat transfer in upward-facing cavities, as for radiation, no correlation was reported.

In this paper, the combined free convection and radiation heat transfer in an upward-facing cylindrical cavity subjected to constant heat flux under different cavity tilt angles, heat fluxes and surface heating conditions are performed experimentally. The reliability of experimental results is evaluated by detailed uncertainty analysis. Then three-dimensional numerical investigation is carried out to figure out the influences of cavity tilt angle and surface heating condition from the aspect of physical mechanism. In the end, the correlations for predicating free convection and radiation heat transfer Nusselt number Nu_c and Nu_r under different surface heating conditions are developed respectively. Considering the fact that the surface heating condition alters frequently in some practical applications, a novel correlation merging the effect of surface heating condition is put forward for the first time. This study will fill the gap of combined free convection and radiation heat transfer in the upward-facing cylindrical cavity.

2. Experimental investigation

2.1. Experimental apparatus

Fig. 2 shows the schematic diagram of experimental setup. Two voltage regulators (TDGC2-3KVA, DELIXI) are used to control the power imposed on the cavity surfaces, and temperature acquisition instruments (XMTA-JK408) are used to record the required temperatures. Besides, cavity tilt angle, which is adjusted by the angle regulator with a resolution of 0.1°, is defined as the angle between the horizontal plane and the normal of aperture plane. The cavity tilt angle is considered as −90° in the vertical upward-facing position, 0° in the sideward-facing position and 90° in the vertical downward-facing position, as shown in Fig. 1.

The cross-section view of cavity in YOZ plane is also shown in Fig. 1. The cavity wall with thickness of 4 mm, is made of 304 stainless steel ($06Cr_{19}Ni_{10}$). The outer surfaces of cavity bottom and side walls are covered with ceramic fiber paper, whose thicknesses are 97.5 mm and 53 mm respectively. The thermal conductivity of the insulation material is dependent on temperature and the relation is expressed as

$$\lambda_i = 7.0704\times10^{-10}(t+273)^3 - 1.24\times10^{-6}(t+273)^2 + 8.9256\times10^{-4}(t+273) - 0.144575 \quad (1)$$

where the fitting data come from Refs. [18,19]. t is the average temperature of insulation layer and this formula is valid for t ranging from 25 °C to 600 °C.