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Numerical investigation on combined natural convection and radiation heat losses in one side open cylindrical cavity with constant heat flux

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ABSTRACT

In the case of considering conduction heat loss through the insulation, a 3D numerical investigation of the combined natural convection and radiation heat losses in one side open cylindrical cavity with constant heat flux has been carried out. Numerical procedure is validated by our latest experimental measurements. Visualization results, i.e., temperature and velocity contours, velocity vector field are provided. The effects of tilt angle, aperture ratio, heat flux as well as surface emissivity on the convection heat loss Nusselt number and radiation heat loss Nusselt number have been quantitatively analyzed. Results show that natural convection heat loss Nusselt number is more sensitive to tilt angle and aperture size, except when the tilt angle is 90° (the opening facing vertically downward), at this point no matter how other parameters change, natural convection heat loss Nusselt number always fluctuates in a small value. While radiation heat loss Nusselt number increases with the increase of all the impact parameters to some extent. The radiation heat transfer weakens the natural convection in the cavity. When the total heat flux is constant, the percentages of three modes of heat losses show different variations with related parameters. In addition, separate empirical Nusselt number correlations for natural convection heat loss and radiation heat loss based on a large set of numerical data for a given range of parameters of practical interest have been proposed.

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1. Introduction

The heat loss characteristics in a cavity with one vertical side open have a wide range of industrial applications, some applications are solar thermal receivers, cooling of electronic devices, energy-saving household refrigerators, ovens in open door conditions, fire spread in buildings, multilayered walls and double windows, brake-housing systems in aircraft, etc. Take solar thermal receiver system for example, the heat losses of the cavity mainly include the radiation heat loss among the interior wall surfaces of the cavity, the convection heat loss from the aperture to the ambient and the conduction heat loss through the insulation.

During the past three decades, several investigations have been presented for describing the phenomenon of natural convection in open cavities and numerous semi-empirical correlations for predicting the convection heat loss have been obtained. A comprehensive review on the research and progress of the convection heat loss from cavity receiver has been carried out by Wu et al. [1]. It is concluded that four shapes of cavity have been investigated experimentally and numerically, namely cubical, rectangular, cylindrical, and hemispherical, among these most attention has been paid to square and rectangular open cavities but fewer have been taken on cylindrical and hemispherical cavities. The Australian national university has involved with the investigation of solar thermal energy conversion using a cylindrical cavity receiver for many years [2–9]. Their studies have focused on the influence of Rayleigh number, cavity geometry, aspect ratios and inclination on the convection heat loss through the aperture, and various correlations for natural convection heat loss prediction have been proposed.

Besides, the heat loss characteristics under different wall boundary conditions have been studied in order to better understand the mechanism of heat loss in cavity. From the review works of Prakash et al. [10] and Juárez et al. [11], it is reported that large volume of the researches [12–23,11] on the heat loss of cavity in the past are limited to the thermal boundary conditions with all cavity walls having the same temperature or the wall facing the opening is isothermal and others are adiabatic. However, when doing the above researches on the solar thermal receiver, it is more realistic to treat the solar radiation as a constant heat flux according to its properties [24–26]. And in most experimental research, the cavity walls are usually heated electrically, hence, constant heat flux boundary condition is closer to actual working condition. In other words, the selection of isothermal boundary condition

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Nomenclature

F_{ij}	view factor from surface i to surface j
h	heat transfer coefficient (W/(m^2 K))
Nu_c	convection heat loss Nusselt number
Nu_r	radiation heat loss Nusselt number
q	heat flux (W/m^2)
T	temperature (K)

Greek symbols

ε	emissivity of the inner wall surface
λ	thermal conductivity (W/(m K))
σ	Stefan–Boltzman constant, 5.67×10^{-8} W/(m^2 K^4)
φ	tilt angle (°)
ΔT	average temperature difference between the inner walls of cavity and ambient (K)

Subscripts

bo	bottom wall
c	convection
r	radiation
exp	experiment
si	side wall

may cause larger deviation from the real heat loss characteristics. Polat and Bilgen [27,28], Bilgen and Oztop [29] and Muftuoglu and Bilgen [30] have numerically studied the natural convection heat transfer in partially open inclined square cavities, the side facing the opening is heated by a constant heat flux while the other sides perpendicular to the heated wall are adiabatic.

Moreover, most of the researches on the convection heat loss have been addressed excluding the radiation heat loss effect, i.e., the contribution due to surface radiation is either absent or ignored. But, since all real surfaces have a non-zero emissivity, the presence of radiation influences the wall temperature to various extents depending on the value of the surface emissivity. The wall temperature in turn influences the natural convection flows such that the radiation and convection contributions may become competitive and thus influence the total heat transfer rate, it is therefore unrealistic to ignore surface radiation interactions in situations such as those mentioned earlier [31]. The importance of the interaction of surface radiation and natural convection can be found in some earlier studies [32–40]. In the last few years, Balaji and Venkateshan [41] have presented that surface radiation alters the basic flow pattern as well as the overall thermal performance of the open cavity. An experimentally parametric study has been carried out by Ramesh and Merzkirch [42] to understand the effect of interaction of surface radiation on natural convection heat transfer of a side-vended open cavity with top opening. It is found that the flow and temperature patterns are significantly influenced by the surface emissivity of the cavity.

Parametric analysis of combined heat losses characteristics have been carried out by a lot of researchers. Singh and Venkateshan [31] have studied the effects of aspect ratio, side-vent ratio and surface emissivity on the combined laminar natural convection and surface radiation heat transfer, separate Nusselt number correlations have been developed for convective and radiative heat transfer based on numerical data. Kumar and Reddy [43] have presented the effects of inclination, operating temperature, the geometry and emissivity on combined natural convection and surface radiation heat transfer of the receiver, and then they further studied the geometry of the cavity on the total heat loss from the receiver [44]. Sharma and Velusamy [45] performed a 2D numerical study of flow and temperature fields for turbulent natural convection and surface radiation, a correlation relevant to practical applications in the form of average Nusselt number, as a function of Rayleigh number, radiation convection parameter and inclination of the enclosure has been proposed. Hinojosa et al. [46] have reported that as inclination of the cavity changes convective Nusselt number changes significantly while the radiation Nusselt number changes negligibly.

Some studies have also addressed the effect of conduction heat transfer along with the combined natural convection and surface radiation heat transfer. Larson and Viskanta [40] have investigated the combined performance of natural convection, conduction and radiation heat losses in a square cavity. It is found that the radiation dominates the heat transfer in the enclosure and alters the convective flow pattern significantly. Balaji and Venkateshan [47] have given a detailed parametric study on the combined conduction, natural convection and radiation heat transfer in a vertical slot (closed end open cavity). Dehghan and Behnia [48] have analyzed the combined natural convection, conduction and radiation heat transfer in an open-top upright cavity. From the comparison of the numerical results with experimental observations, the accurate prediction of the flow and thermal fields is strongly dependent on the consideration of radiation heat transfer. Nouanegue et al. [49] have investigated the conjugate heat transfer by natural convection, conduction and radiation in an open cavity, it is found that surface radiation affects the flow and temperature fields of the cavity considerably.

Recently, we have carried out an experimental investigation to find out the effects of surface boundary conditions on heat losses of a fully open cylindrical cavity [50]. However, to the authors' best knowledge, in the case of considering the conduction heat loss through the insulation, the 3D numerical investigation on the combined natural convection and radiation heat losses of a partly open cylindrical cavity with wall surfaces heated by constant heat flux has not been addressed in literature yet. This paper will provide further information on the natural convection heat loss and radiation heat loss of cylindrical cavity where all the cavity walls are heated by constant heat flux, parameters such as the tilt angle φ, aperture ratio AR, heat flux q and surface emissivity ε will be considered.

2. Physical and numerical models

2.1. Physical model and assumptions

Fig. 1 shows the physical model of the open cylindrical cavity under consideration for the combined heat transfer. The outer surface of the cavity is covered with insulation to reduce the conduction heat loss. Besides, there is a cover plate on the opening. The materials of the cavity, insulation and cover plate are stainless steel, ceramic fiber and calcium silicate, respectively. The cavity has inner diameter of 105 mm, depth of 161.5 mm including the wall thickness of 4 mm. The tilt angle φ is defined as 0° when the aperture facing horizontally and 90° when facing vertically downward. All the cavity walls are heated by constant heat flux.

The dimensionless aperture size is defined as the ratio of aperture diameter d to the inner diameter D, to investigate the impact of aperture size. The inner diameter D keeps constant while the diameter of aperture d alters from 52.5 to 105 mm.

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