International Journal of Thermal Sciences 124 (2018) 122–130

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Turbulent natural convection combined with thermal surface radiation inside an inclined cavity having local heater

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ARTICLE INFO

Keywords:
Thermal surface radiation
Turbulent natural convection
Inclined cavity
Local heater
Numerical results

ABSTRACT

A numerical study of turbulent natural convection with thermal surface radiation inside an inclined square enclosure with a local heat source has been performed. The main attention is paid to the effect of the inclination angle on the fluid flow and heat transfer. Two-dimensional equations of conservation of mass, momentum and energy using the k–ε turbulence model have been solved by finite difference method. Localized heating has been simulated by a centrally located heat source on the bottom wall. The angle of inclination, changed from 0 to π, is used as a control parameter for heat transfer. A detailed numerical analysis has been conducted for a wide range of Rayleigh number of 10^8–10^{10} and surface emissivity $0 \le \tilde{\varepsilon} \le 0.9$. The results show that a growth of the cavity inclination angle leads to a reduction of radiative Nusselt number. In general, it was found that the values of Rayleigh number, inclination angle and surface emissivity have significant effect on the temperature and stream function contours within the enclosure. Therefore, these parameters can be very good control parameters for fluid flow and heat transfer inside the cavity. The developed numerical method and obtained results can be widely used in different engineering problems, e.g. the simulation of air flow and heat transfer from heat-generating elements in power engineering. Moreover, the obtained results provide better technical support for development and research of electronic cooling systems.

1. Introduction

The numerical and experimental investigations of natural convection heat transfer in enclosures have primarily been devoted to the two limiting cases: the configuration of an enclosure heated and cold from the vertical sides and the classical Rayleigh-Benard problem. Nevertheless, in many practical situations, enclosures are inclined to the direction of gravity [1–3]. Hence, to solve this problem need to consider both components of buoyancy forces (normal and tangential) which strongly influence on the fluid flow and heat transfer in enclosure.

The main regularities in experimental and numerical studies of natural convection flow in inclined cavities have been discussed in review articles of Yang [4]. Ozoe et al. [5] experimentally have studied laminar natural convection in a long rectangular channel at different Prandtl numbers. The authors have reported that the angle of inclination at critical conditions is a strong function of the aspect ratio and a weak function of the Rayleigh number. The effect of inclination angle on steady natural convection in an enclosure has been investigated by Rasoul and Prinos [6]. They have found that the mean Nusselt number increases with increasing Rayleigh number for all inclination angles examined. Moreover, the maximum local Nusselt number has been observed close to bottom position for angles greater than $\pi/2$. Experimental and numerical study of Hamady et al. [7] deals with natural convection in an air-filled differentially heated enclosure at various inclination angles and Rayleigh numbers from 10^4 to 10^6. It should be mentioned that the heat flux at the hot and cold boundaries show strong dependence on the angle of inclination and the Rayleigh number. Adjlout et al. [8] have investigated natural convection in an inclined cavity with a wavy wall. Their findings indicated that an increase in the undulation number on the hot wall reduces the heat transfer rate for an inclination angle greater than $5\pi/12$. Nouanegue et al. [9] have studied conjugate heat transfer by natural convection, conduction and radiation in an inclined square enclosure. They have showed that the convective heat flux is a strongly decreasing function of the surface emissivity. Also, due to the influence of surface radiation, the convective Nusselt number is increased for low inclination angle and decreased at high inclination angle. Yedder and Bilgen [10] have investigated laminar natural convection in an enclosure bounded by a solid wall. Their results have shown that heat transfer rate is an increasing function of wall

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http://dx.doi.org/10.1016/j.ijthermalsci.2017.09.023
Received 19 February 2017; Received in revised form 28 September 2017; Accepted 30 September 2017

conductivity ratio, enclosure aspect ratio, Rayleigh number and a decreasing function of the solid wall thickness. Numerical study of natural convection phenomenon in an inclined cube has been performed by Ravnik et al. [11]. They have shown that 2D calculated Nusselt number values are quite close (within 8%) to the Nusselt number values obtained using 3D simulation. Lo et al. [12] also have studied natural convection in an inclined cubical cavity. It has been found that an increase in the cavity inclination angle leads to the buoyancy force decrease resulting in poor free convection phenomenon inside the cavity. A two-dimensional numerical simulation of turbulent and laminar natural convection in an inclined square cavity has been performed by Kuyper et al. [13]. In their study, the Nusselt number shows strong dependence on the orientation of the cavity and the power-law dependence on the Rayleigh number of the flow. Mushatet [14] has investigated turbulent natural convection inside an inclined square cavity having two conducting solid baffles. Obtained results have indicated that the rate of heat transfer decreases then both cavity inclination angle increases and the relative baffles height decreases. The work of Sharma et al. [15] deals with two-dimensional numerical studies of flow and temperature fields for turbulent natural convection and thermal surface radiation in inclined differentially heated enclosures. Their findings have indicated that the turbulent viscosity is maximum at the center of the enclosure for zero inclination angle and as inclination angle increases, it reduces at the center and increases around the wall zones. Sharif and Liu [16] have studied numerically turbulent natural convection in a two-dimensional side-heated square cavity at various angles of inclination using both k–ε and k–ω turbulence models. They have shown that the variation of local Nusselt numbers at the heated walls shows monotonic change for inclination angle less than $\pi/4$ and oscillatory variation near the upstream corners for inclination angle greater than $\pi/4$. Vivek at al [17]. have investigated numerically the effects between surface radiation and natural convection in air filled tilted enclosures. The hot and cold walls of enclosure were maintained isothermal while the other two walls were adiabatic. It was found that the interaction effects between radiation and convection are very strong in shallow enclosures compared to square enclosures. Moreover, useful engineering correlations of the total Nusselt number depending on the inclination angle of the enclosure, Rayleigh number, emissivity and temperature ratio have been obtained. Patil et al. [18] have studied laminar natural convection combined with thermal surface radiation in a differentially heated square cavity with broad protrusions of different positions and shapes. They found that the secondary flow formed owing to the protrusions, helps to enhance natural convection circulation inside the cavity. Montiel-González et al. [19] have theoretically and experimentally examined heat transfer by natural convection and thermal radiation on a solar open cubic cavity-type receiver. It was revealed that for analyzed Rayleigh numbers, the consistency of flow pattern and temperature field obtained considering the variable properties and the Boussinesq approximation is good for the dimensionless temperature difference (0.033 and 0.333). However for a larger temperature difference, the variation higher than 10%. Hinojosa et al. [20] have analyzed numerically entropy generation in a square open cavity with natural convection and surface thermal radiation. They found that surface thermal radiation increases the overall entropy generation rate between 33.52% and 560.87%, and thus cannot be neglected in the analysis of this type of system.

The position of local heaters also plays an important role in determining the nature of the flow and heat transfer. Due to its importance in various applications, a large number of experimental and numerical studies have been carried out in the last decade [21–23]. Saravanan and Sivaraj [24] have investigated the interaction between natural convection and thermal radiation in a square cavity with a discrete heater placed inside. They have considered both isothermal and heat generating types of the heater. Their results have shown that the overall heat transfer rate is enhanced with an increase in the surface emissivity and the Rayleigh number for both isothermal and heat generating heaters. The initial stage of formation of convective plumes emerging from finite size heat sources has been investigated experimentally by Kondrashov et al. [25]. They have examined two scenarios (convective and conductive) of thermal plume organization. According to the results of experiments, there are two main ways to organize a convective plume, viz., thermal conduction and convection methods.

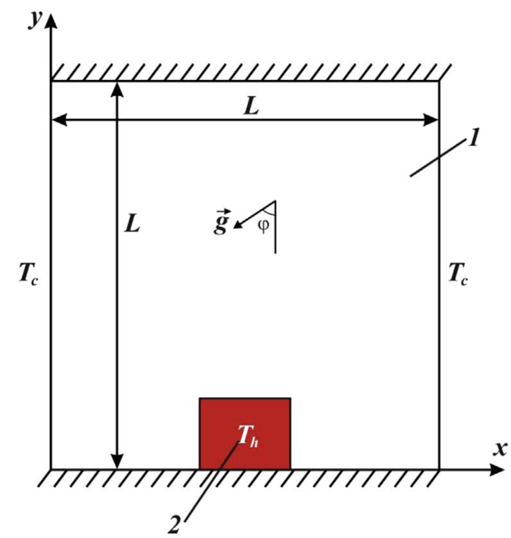

Fig. 1. The domain of interest: *1*–air, *2*–local heater.

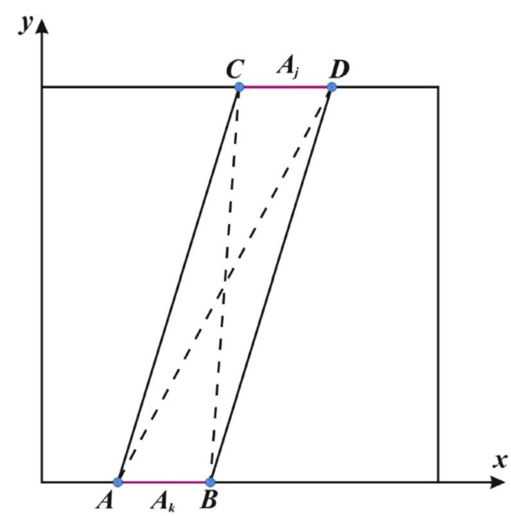

Fig. 2. Illustration of Hottel crossed string method.

Despite a large number of numerical and experimental studies on inclined enclosures described in the literature, there is still a lack of information regarding the problem of turbulent natural convection with thermal surface radiation in an inclined cavity having local heaters. To the authors' knowledge this is the first thorough turbulence study deals with an inclined cavity containing among others a local heat source. The main aim of the present work is to examine the influence of inclination angle, surface emissivity and Rayleigh number on turbulent heat transfer and fluid flow in considered area with a local heater. Numerical formulation, solution procedure and results are presented in the following sections. It is worth noting, that the considered problem has an essential engineering application concerning a development of optimal cooling system for heat-generating sources in electronics and energy systems. The examined heater is a constant temperature source, but such analysis is necessary for physical understanding an interaction between convective heat transfer and thermal radiation under local heating in an inclined cavity. Further, we are going to study the effect