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Conjugate mixed convection in a rectangular cavity with a local heater

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A B S T R A C T

Mixed convection in an open cavity having solid walls of finite thickness and conductivity under the effect of local heaters has been studied. The domain of interest is considered as an electronic cabinet having heat-generating chips with active cooling system. Mathematical description of analyzed physical process has been carried out on the basis of two-dimensional partial differential equations with corresponding initial and boundary conditions that have been formulated in dimensionless stream function, vorticity and temperature. Boundary-value problem has been solved by finite difference method. A numerical analysis has been carried out for $Pr = 0.7$, $Re = 100$ and a wide range of Richardson number ($Ri = 0.01$–10.0), heater location (left and right walls with bottom, central or upper position) and heater size ($h_2/L = 0.3$–0.6) in order to understand the effectiveness of modeled active cooling system.

1. Introduction

Convective heat and mass transfer processes are realized in natural and technical systems, including transport of contaminants, cooling of electronic devices, solar collectors, thermal behavior in buildings, and many others. Nowadays, a creation of effective cooling systems for electronic devices is a major task for development of different industrial fields. It should be noted that a solution of this problem demands a detailed simulation of momentum transport, heat and mass transfer processes in a wide range of governing parameters, taking into account additional mechanisms inside solid walls or heaters [1–3].

Several theoretical and experimental papers are published on this topic. Thus, Rao and Narasimham [4] have analyzed numerically conjugate mixed convection in a vertical channel with heat-generated local sources. It has been found that simple adiabatic boundary condition for the substrate and isothermal or isoflux condition for the heat source are not appropriate and that the conjugate nature of the problem should be considered taking into account the heat conduction in both the components and the substrate. Tso et al. [5] have investigated numerically and experimentally laminar natural convection cooling of water in a rectangular cavity with a set of local heaters on the wall under the effect of the cavity inclination angle. The authors have revealed that in the horizontal orientation, with a growth of Rayleigh number, the flow pattern evolutions are complex and identified with three main characteristics: from toroidal convection to bimodal convection to Rayleigh–Benard convection. At the same time the horizontal orientation is best because the lowest average Nusselt number among the three considered rows of heaters is higher than those of other orientations. Muftuoglu and Bilgen [6] have defined numerically the optimum positions of local heaters along the left vertical wall in a semi-open square cavity. The optimum positioning has been obtained by maximizing the global performance and it is not uniform location with equidistance between them. Yang and Wu [7] have studied numerically conjugate mixed convection in the entrance of a vertical channel of finite thickness heat-conducting solid walls in the case of external temperature load. It has been found that the average Nusselt number at the solid-fluid interface increases with the growth of thermal conductivity ratio and reduction of the solid wall thickness. Papanicolaou and Jaluria [8,9] have examined mixed convection in an open cavity with heat-conducting solid walls and heat-conducting local heaters of constant heat generation. The effects of heaters location (central position at left, right and bottom walls) and Richardson number have been analyzed. It has been found that the location of heater on the right vertical wall is the most favorable for cooling. Also it has been revealed that at a certain amount of heat input by the heaters, oscillatory flow and thermal fields may develop in the cavity. Khanafer and Chamkha [10] have studied mixed convection of a fluid-saturated porous medium in a horizontal annulus under the effect of internal heat generation. They have found that the Richardson number has a significant effect on the flow patterns within the annulus with respect to two-eddy, one-eddy and no-eddy flows. Ben-Nakhi and Chamkha [11] have investigated numerically conjugate natural convection around a finned pipe placed in the center of a square cavity with uniform heat generation. It has been found that the finned pipe inclination angle, fins length, and external and internal Rayleigh numbers have

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Nomenclature

Roman letters

g	gravitational acceleration
H	height of the channel
h_1, h_2, h_3, h_4	distances along the vertical coordinate for the heater location
k	thermal conductivity
L	length of the channel
l_1	thickness of the left solid wall
l_2	length of the cavity
Nu	Nusselt number
p	dimensional pressure
Pr	Prandtl number
Ra	Rayleigh number
Re	Reynolds number
Ri	Richardson number
T	dimensional temperature
t	dimensional time
T_c	inlet air temperature
T_h	heater temperature
U, V	dimensionless velocity components
u, v	dimensional velocity components
u_{in}	air inlet velocity
X, Y	dimensionless Cartesian coordinates
x, y	dimensional Cartesian coordinates

Greek symbols

α	thermal diffusivity
β	thermal expansion coefficient
Θ	dimensionless temperature
μ	dynamic viscosity
τ	dimensionless time
ρ	density
Ψ	dimensionless stream function
Ω	dimensionless vorticity

Subscripts

avg	average
c	cold
f	fluid
h	hot
in	inlet
w	wall
wf	wall/fluid ratio

significant effects on the local and average Nusselt number at the enclosure wall-cavity and finned pipe–cavity interfaces. Oztop et al. [12] have performed a numerical study on natural convection heat transfer in a wavy-walled cavity with volumetric heat sources. They have revealed that both the function of wavy wall and the ratio of internal Rayleigh number to external Rayleigh number affect the heat transfer and fluid flow significantly. Chamkha and Ismael [13] have analyzed numerically conjugate natural convection heat transfer in a square porous cavity filled with a water-based nanofluid heated by a triangular solid wall. It has been shown that the heat transfer can be increased with increasing the value of the triangular wall thickness. Therefore, heat conduction in solid walls can play an essential role in convective heat transfer. Steady and unsteady laminar flow and heat transfer in a channel with an open square cavity of heated bottom wall has been examined using LBM and Fluent software by Burgos et al. [14]. They have obtained a good agreement between different numerical approaches. The obtained data have shown that for high Richardson numbers the recirculation is no longer encapsulated, the flow becomes unsteady, and an oscillatory instability develops. At the same time, the unsteady regimes have revealed a very rich phenomenology where the geometry of the problem couples with the oscillatory thermal instability. Hamouche and Bessaih [15] and Boutina and Bessaih [16] have analyzed numerically mixed convection air-cooling of two heat sources mounted in a horizontal [15] and inclined [16] channels. On the basis of finite volume method it has been revealed that a growth of separation distance, the height and the width of the electronic components leads to an essential enhancement of the heat removal rate from the components. More considerable cooling of electronic components has been found for inclined channel. Bahlaoui et al. [17] have studied numerically mixed convection combined with thermal surface radiation within a horizontal ventilated cavity heated from below and provided with an adiabatic thin partition on the heated wall. The authors have shown that the radiation effect leads to a better homogenization of the temperature inside the cavity by reducing the cold zone space in the entrance region. Transient laminar mixed convective heat transfer from two flush-mounted discrete heat sources has been investigated numerically for an inclined rectangular channel [18] and experimentally for a vertical rectangular cavity [19] using water as a working fluid. It has been found that for the horizontal configuration of the cavity, due to the indirect effect of buoyancy force, much higher threshold values of buoyancy strength are required for the appearance of the recirculation flows that take place downstream of the heated slabs. Abdelmassih et al. [20] have extended the investigation of Burgos et al. [14] to the case of steady and unsteady mixed convection flow in a cubical cavity located at the bottom of a square channel. Numerical and experimental techniques have been used for the considered problem. Three flow regimes have been revealed such as steady, periodic and turbulent flow for the considered range of governing parameters. Ben-Nakhi and Chamkha [21] have examined numerically conjugate natural convection in a square enclosure with an inclined thin fin of arbitrary length. It has been found that the thin fin inclination angle, length and solid-to-fluid thermal conductivity ratio have significant effects on the local and average Nusselt numbers at the heated surfaces of the cavity. Conjugate natural convection in a square nanofluid cavity with sinusoidal temperature variations on both horizontal walls has been analyzed by Alsabery et al. [22] using the heatlines technique. It has been shown that the heat transfer rate is significantly enhanced by a growth of the solid wall thickness. Different values of the thermal conductivity ratio are shown to depict a variety of enhancements for the heat transfer rate. Chamkha [23] have studied hydromagnetic fully developed laminar mixed convection flow in a vertical channel with symmetric and asymmetric wall heating conditions in the presence or absence of heat generation or absorption effects. Analytical solutions for the velocity and temperature profiles for various special cases of the problem have been obtained. It has been shown that no reverse flow occurs for the case of symmetric channel wall temperatures while reversal flow near the walls is assured for asymmetric channel wall temperatures and mixed isoflux–isothermal or isothermal–isoflux wall thermal conditions. The zone of assured reversal flow has been found to increase owing the presence of either of the magnetic field or the heat generation effects or both. Ismael et al. [24] have investigated entropy generation due to conjugate natural convection in a square porous cavity filled with a CuO/water nanofluid under the effect of a triangular heat-conducting solid block. The performed analysis has shown that for a high conductivity solid wall, the overall heat transfer and the global entropy generation rate increase faster than those of a low conductivity solid wall. RamReddy et al. [25] have presented results for the Soret effect on mixed convection in the boundary layer region of a semi-infinite vertical flat plate in a nanofluid under the convective boundary conditions. Authors have shown that the skin friction, heat, nanoparticle mass and regular mass transfer rates are enhanced with increasing values of mixed convection parameter. Kuznetsov and Sheremet [26] have studied numerically conjugate mixed convection in a rectangular cavity with solid walls of finite thickness and conductivity in the presence of a local heater. The authors have obtained the heat convection modes diagram for different values of Grashof and Reynolds numbers. Ismael and Chamkha [27] have an-