Case Studies in Thermal Engineering 10 (2017) 100–110

Contents lists available at ScienceDirect

Case Studies in Thermal Engineering

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

Numerical study of three-dimensional natural convection and entropy generation in a cubical cavity with partially active vertical walls

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A R T I C L E I N F O

Keywords:
Natural convection
Cubical cavity
Three-dimensional flow
Entropy generation
Partially active vertical walls

A B S T R A C T

Natural convection and entropy generation due to the heat transfer and fluid friction irreversibilities in a three-dimensional cubical cavity with partially heated and cooled vertical walls has been investigated numerically using the finite volume method. Four different arrangements of partially active vertical sidewalls of the cubical cavity are considered. Numerical calculations are carried out for Rayleigh numbers from ($10^3 \le Ra \le 10^6$), various locations of the partial heating and cooling vertical sidewalls, while the Prandtl number of air is considered constant as $Pr = 0.7$) and the irreversibility coefficient is taken as ($\varphi = 10^{-4}$). The results explain that the total entropy generation rate increases when the Rayleigh number increases. While, the Bejan number decreases as the Rayleigh number increases. Also, it is found that the arrangements of heating and cooling regions have a significant effect on the fluid flow and heat transfer characteristics of natural convection and entropy generation in a cubical cavity. The Middle-Middle arrangement produces higher values of average Nusselt numbers.

1. Introduction

Natural convection or buoyancy-driven heat transfer and fluid flow in enclosures are an important subject in engineering applications such as double pane windows, semi-conductor production, nuclear reactor cores, electronic equipment cooling, solar energy technologies, etc. It has been considered a subject of very active research works over the past years and a good reviews on it were performed by Ostrach [1], Khalifa [2] and very recently by Polezhaev et al. [3]. In the published literature, various research works have been related with the natural convection in enclosures under various boundary conditions. November and Nansteel [4] performed an analytical and numerical studies on natural convection heat transfer in rectangular enclosure filled with water. The enclosure was heated from below and cooled on one vertical side. Aydin et al. [5] simulated numerically the natural convective heat transfer of air in a square cavity symmetrically cooled from one side wall and heated by a strip placed at the bottom of the central wall. The effect of the heated strip width with the Rayleigh number was also investigated. Deng et al. [6] presented a numerical study on a two-dimensional, steady and laminar natural convection in a rectangular enclosure with discrete heat sources on walls. They

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http://dx.doi.org/10.1016/j.csite.2017.05.003
Received 11 April 2017; Received in revised form 2 May 2017; Accepted 7 May 2017
Available online 08 May 2017

Nomenclature

Be	Bejan number
g	Gravitational acceleration (m/s^2)
k	Thermal conductivity (W/m K)
l	Cavity width and height (m)
n	Unit vector normal to the wall.
N_s	Dimensionless local generated entropy
Nu	Local Nusselt number
Pr	Prandtl number
$\vec{q}$	Heat flux vector (W/m^2)
Ra	Rayleigh number
S'_{gen}	Generated entropy per unit volume (W/m^3 K)
t	Dimensionless time ($t'. \alpha/l^2$)
T	Dimensionless temperature $[(T' - T'_c)/(T'_h - T'_c)]$
T'_c	Cold temperature (K)
T'_h	Hot temperature (K)
T_o	Average temperature $[T_o = (T'_c + T'_h)/2]$
$\vec{V}$	Dimensionless velocity vector ($\vec{V}'. l/\alpha$)
x, y, z	Dimensionless Cartesian coordinates (x'/l, y'/l, z'/l)

Greek symbols

α	Thermal diffusivity (m^2/s)
β	Thermal expansion coefficient (1/K)
μ	Dynamic viscosity (kg/m s)
ν	Kinematic viscosity (m^2/s)
φ	Irreversibility coefficient
$\vec{\psi}$	Dimensionless vector potential ($\vec{\psi}'/\alpha$)
$\vec{\omega}$	Dimensionless vorticity ($\vec{\omega}'. \alpha/l^2$)
ΔT	Dimensionless temperature difference
ϕ'	Dissipation function

Subscripts

Av	Average
x, y, z	Cartesian coordinates
fr	friction
th	thermal
tot	total

Superscript

$'$	Dimensional variable

concluded that the suggested combined temperature scale were efficient to characterize the various roles of the heat sources and to provide an effective approach to analyze more realistic and complex natural convection problems. Corcione [7] performed a numerical investigation on natural convection in air-filled, two-dimensional rectangular enclosures heated from below and cooled from above with wide variety of thermal boundary conditions at the side walls. However, the subject about partially heated or cooled walls is more recent, and also, for a given geometry, the number of boundary conditions that can be studied is really infinite. This is the reason why published papers concerning cavities with partially active walls are still not too much. Valencia and Frederick [8] presented a numerical investigation on the heat transfer of air in square cavities with partially active vertical walls. Paroncini et al. [9,10] investigated experimentally and numerically the natural convective heat transfer in a square enclosure with partially active sidewalls. Corvaro et al. [11] presented an experimental PIV and interferometric analysis of natural convection in a square cavity filled with air at atmospheric pressure. Two strips (cold and hot) were applied on the vertical sides of the enclosure. Tests involved three different configurations, with the hot strip in the middle of one wall, and the cold strip at the bottom, in the middle or at the top of the opposite wall. Results showed that the configuration with the cold strip at the top of the wall produced the fastest dynamic field and the highest Nusselt number. Very recently, Paroncini et al. [12] presented an experimental and numerical analysis on natural convection of air in square enclosures with partially active side walls. The experimental study was carried out both through the holographic interferometry in order to obtain the average Nusselt numbers at different Rayleigh numbers. The temperature distributions in the air and the heat transfer coefficients were measured by a holographic interferometry and compared with the numerical results that were obtained with the finite volume code Fluent 12.1.4. From the other side, the three-dimensional natural convection in enclosures was investigated by many authors. Fusegi et al. [13] performed a numerical study of three-dimensional natural convection flows of a viscous fluid in a differentially heated cubical enclosure. The vertical sidewalls of the enclosure were maintained at constant temperatures of different values. The other vertical walls were considered thermally insulated. Results were presented for Rayleigh numbers of 10^5 and 10^6. They concluded that the predicted velocity and temperature profiles in the symmetry planes were consistent with experimental measurements. Fusegi et al. [14] investigated numerically the three-dimensional natural convection in a differentially heated cubical enclosure. The enclosure walls were assumed to be adiabatic. They found that the Nusselt number for the three-dimensional cube was smaller than that for the two-dimensional square for Ra $< 10^5$. Sezai and Mohamad [15] performed a numerical simulation of three-dimensional natural convection in the open cavity heated from the opposite vertical wall and the results were compared with 2-D simulations. The results showed that there was a difference in the Nusselt number predicted by the two models for Rayleigh numbers equal to 10^5 and above. They indicated that the three-dimensional simulations were necessary for open cavities at Rayleigh numbers above 1×10^5. Frederick and Berbakow [16] numerically investigated the natural convection in a cubical enclosure with a hot source centered on a vertical wall and with an adjacent, fully cooled vertical wall for Rayleigh numbers of $10^3 - 4 \times 10^6$. The results indicated that at (Ra $< 10^5$) the heat transfer strongly depended on the hot sector side and its dependence on the Rayleigh number was weak. Opposite characteristics occurred at very high Rayleigh number, and there was a long transition between these two regimes. **Lo** and Leu [17] applied the differential quadrature method to simulate natural convection in an inclined cubic cavity using velocity-vorticity formulation. The results were obtained for different angle of inclinations, for Rayleigh number equals to 10^3, 10^4, 10^5 and 10^6. They concluded that their method was capable of solving coupled Navier-Stokes equations effectively and accurately. Other useful researches related with the three-dimensional natural convection in