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Numerical analysis of entropy generation due to natural convection in three-dimensional partially open enclosures

Hakan F. Oztop [a,d,*], Lioua Kolsi [b,c], Abdulaziz Alghamdi [b], Nidal Abu-Hamdeh [d], Mohamed Naceur Borjini [c], Habib Ben Aissia [c]

[a] Department of Mechanical Engineering, Technology Faculty, Firat University, Elazig, Turkey
[b] Department of Mechanical Engineering, College of Engineering, Haïl University, Haïl, Saudi Arabia
[c] Unité de Recherche de Métrologie et des Systèmes Energétiques, Ecole Nationale d'Ingénieurs, University of Monastir, 5000 Monastir, Tunisia
[d] Department of Mechanical Engineering, King Abdulaziz University, Jeddah, Saudi Arabia

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ABSTRACT

Three-dimensional computational analysis of entropy generation due to natural convection in partially open enclosure has been performed in this work by using finite volume method. A written computer code was developed to solve governing equations of this three-dimensional problem. The study has been performed for different governing parameters such as opening ratio $0.25 \le h \le 0.75$, center of opening $0.25 \le d \le 0.75$ and Rayleigh number $10^3 \le Ra \le 10^5$. It is observed that edge of openings is the most effective parameter on entropy generation and after comparing many cases, both the highest heat transfer and entropy generation were observed for the fully opened cavity.

1. Introduction

Natural convection in open enclosures has considerable interest in several engineering applications such as cooling of electronic equipment, cooling and heating of buildings, solar heaters or vehicles. Energy consumption on these systems is very important from the energy efficiency point of view. One of the bases of the design of such engineering systems is the analysis of irreversibility sources.

These systems are mostly analyzed in two-dimensional configurations but 3D effects are often predominant and give a better understanding the phenomena. Among the two-dimensional studies, Kefayati et al. [1] used the Lattice Boltzmann simulation to simulate the natural convection in an open enclosure which subjugated to water based copper nanofluid. Authors showed that the mean Nusselt number decreases as the aspect ratio increases at various Ra numbers and different nanoparticles volume fractions. Saleem et al. [2] performed a numerical solution to conduct the influence of thermocapillary forces on the natural convection and entropy generation in an open two dimensional enclosure by using Alternate direct implicit (ADI) method. They observed that entropy generation rate increases with the increase in the Marangoni number. Holzbecher [3] made a work on free convection in open-top ended systems which are filled with porous medium. In his case, mixed boundary condition is applied and the onset of convection, total heat and mass transfer, and the transition from the first to the second mode were examined.

Among the three-dimensional studies, Zamora and Kaiser [4] studied the natural convection in cubical open cavities. Their main aim is to make comparison study of 3D simulations with those previously obtained for 2D situations. They used DNS model to make turbulent simulation of heat transfer and fluid flow for variable boundary conditions. A systematic comparisons between the obtained results for 3D and those previously obtained for 2D situations have been carried out, showing that some differences are particularly relevant, such as the evolution of the temperature and Nusselt Number. In their work, they did not taken into account the thermodynamic analysis. Gangawane et al. [5] studied natural convection in a partial heater located open ended square cavity by solving governing equations via lattice Boltzmann method for different Prandtl numbers. They observed that there is a linear increasing on heat transfer rate with Prandtl number and they also obtained empirical correlations. Oztop [6] worked on a mixed convection problem to investigate the influence of exit opening location in a channel with volumetric heat sources but it is in two-dimensional domain. Bilgen and Oztop [7] performed a study of natural convection in partially open inclined square cavities using finite volume technique for two-dimensional solution. They found

* Corresponding author at: Department of Mechanical Engineering, Technology Faculty, Firat University, Elazig, Turkey.
E-mail addresses: hfoztop1@gmail.com, hakanfoztop@gmail.com (H.F. Oztop).

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Nomenclature

Be	Bejan number
Cp	specific heat at constant pressure (J/kg K)
d'	center of location of opening
g	gravitational acceleration (m/s^2)
h	dimensionless opening length, h'/l'
k	thermal conductivity (W/m K)
l	dimensionless cavity width
N_s	dimensionless local generated entropy
Nu	local Nusselt number
Nu_{av}	average Nusselt number
Pr	Prandtl number
Ra	Rayleigh number
S'_{gen}	generated entropy (kJ/kg 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	bulk temperature $[T_o=(T'_c+T'_h)\ /\ 2]$ (K)
$\vec{V}$	dimensionless velocity vector ($\vec{V}'.l/\alpha$)
$\dot{V}$	dimensionless volume flow rate
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)
φ	irreversibility coefficient
θ	fin inclination
ρ	density (kg/m^3)
μ	dynamic viscosity (kg/m s)
ν	kinematic viscosity (m^2/s)
$\vec{\psi}$	dimensionless vector potential ($\vec{\psi}'/\alpha$)
$\vec{\omega}$	dimensionless vorticity ($\vec{\omega}'.\alpha/l^2$)
ΔT	dimensionless temperature difference

Subscripts

av	average
x, *y*, *z*	Cartesian coordinates
fr	friction
th	thermal
tot	total

Superscript

′	dimensional variable

that inclination angle is the most important parameter on volumetric flow rate and heat transfer. Polat and Bilgen [8,9] performed two-dimensional studies on conjugate heat transfer in inclined open shallow cavities by including thickness of the wall and they made the similar work for thin walled open cavities. In both cases, they indicated that open cavity problem is a highly sensitive problem for numerical calculations. Nouanegue et al. [10] solved heat transfer problem for open cavities including natural convection, conduction and radiation. Other studies on natural convection in open cavities can be found in literature as in Ref. [11]. None of these work consider thermodynamic analysis.

Based on Bejan's statement the second law analysis focusing on the entropy generation and its minimization can be applied to convective flow and heat transfer [12]. Entropy generation problem for three-dimensional cubic cavities due to natural convection is studied only by a few papers in literature. In this regards, Oztop and Al-Salem [13] performed a review work on entropy generation and its application in different energy systems. Oztop et al. [14] worked on three-dimensional analysis of combined buoyancy and thermocapillary convection and entropy generation by using finite volume method. There is a few works in literature on entropy generation in open cavities. Mehrez et al. [15] illustrated the entropy generation analysis for mixed convection flow in an inclined open cavity. Their results showed that the flow field, the temperature distribution, the heat transfer and the entropy generation rates are strongly affected by the inclination angle. Other related papers can be found in Refs. [16–19].

Recently, Kolsi et al. [20] studied numerically the 3D flow, heat transfer and entropy generation in a nanofluid filled cavity with solid insert at the corners using finite volume method. Three cases are studied based on number and location of solid inserts. It was observed that three-dimensional solution brings more understanding work for the study. Higher heat transfer and entropy generation are observed in case of nanoparticle addition into base fluid. Authors mentioned that insertions can be used as control element for heat and fluid flow and energy consumption. As continuity of their 3D analysis, Kolsi et al. [21] performed a computational study of natural convection and entropy generation in a sharp edged finned cubic cavity. The main findings of this work are that edge of the fin is extremely effective on entropy generation and Bejan number and high values of thermal conductivity ratio has no tangible effect on entropy generation due to heat transfer and Bejan number.

The main aim of this work is to study on entropy generation due to natural convection in a partially open cavity. Based on authors' knowledge and survey of open literature it is first attempt on analysis of 3D solution of partially open cubic enclosure. The study is important because it investigates the effects of opening ratio on natural convection heat transfer in three-dimensional domains. Comparison of results of the present work with earlier works shows that three-dimensional solution is highly important to understand the flow structure.

2. Model

A three-dimensional model is considered in this work as shown in Fig. 1(a) and (b) for isometric three-dimensional model and detailed view of *X*–*Y* plan to make comparison, respectively. The right side of the cavity is open partially with h' and its center is shown by d'. In this geometry, the gravity act in – *y* direction. The cavity is heated from left side and remaining walls are taken as adiabatic.

3. Theory

Formalism ($\vec{\psi}-\vec{\omega}$) which are respectively defined by the two following relations, is used:

$$\vec{\omega}' = \vec{\nabla}\times\vec{V}' \text{ and } \vec{V}' = \vec{\nabla}\times\vec{\psi}' \tag{1}$$

The setting in equation is described with more details in the paper of Lioua et al. [16]. In the dimensionless form, the system of equations controlling the phenomenon becomes as

$$-\vec{\omega} = \nabla^2\vec{\psi} \tag{2}$$

$$\frac{\partial\vec{\omega}}{\partial t} + (\vec{V}.\nabla)\vec{\omega} - (\vec{\omega}.\nabla)\vec{V} = \Delta\vec{\omega} + Ra.Pr.\left[\frac{\partial T}{\partial z}; 0; -\frac{\partial T}{\partial x}\right] \tag{3}$$

$$\frac{\partial T}{\partial t} + \vec{V}.\nabla T = \Delta T \tag{4}$$

Dimensionless numbers are presented as

$$Pr = \frac{\nu}{\alpha} \text{ and } Ra = \frac{g.\beta.\Delta T.l'^3}{\nu.\alpha} \tag{5}$$

Boundary conditions for considered model are given as follows

Temperature:

$$T = 1 \text{ at } x = 0 \tag{6}$$