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Entropy generation based approach on natural convection in enclosures with concave/convex side walls

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ABSTRACT

Computational study of natural convection within differentially heated enclosures with curved (concave/convex) side walls is carried out via entropy generation analysis. Numerical simulation has been carried out for various Prandtl numbers ($Pr = 0.015$ and 1000) and Rayleigh numbers ($10^3 \leqslant Ra \leqslant 10^5$) with different wall curvatures. Results are presented in terms of isotherms (θ), streamlines (ψ), entropy generation due to heat transfer (S_θ) and fluid friction (S_ψ). The effects of Rayleigh number on the total entropy generation (S_{total}), average Bejan number (Be_{av}) and global heat transfer rate ($\overline{Nu_r}$) are examined for all the cases. Maximum values of S_θ ($S_{\theta,max}$) are found at the middle portion of the side walls for concave cases, whereas, $S_{\theta,max}$ is observed near the top right and bottom left corner of the cavity for convex cases. On the other hand, $S_{\psi,max}$ is seen near the solid walls of the cavity for all concave and convex cases. At all *Ra* and low *Pr*, largest heat transfer rate and lesser entropy generation is found for case 3 (highly concave case). Overall, for convex case, case 1 or case 2 (lesser convex cases) are efficient for all *Ra* and *Pr*. On the other hand, case 3 of concave case (highly concave) offers larger heat transfer rate and lesser entropy generation compared to less concave and all convex cases at low *Ra* and all *Pr*. At high *Ra* and low *Pr*, case 3 (concave) may be the optimal case whereas, at high *Ra* and high *Pr*, case 1 (less concave) may be recommended based on higher heat transfer rate. A comparative study of the concave and convex cases also revealed that the concave cases with high concavity (case 3) may be chosen as the energy efficient case at high *Ra* and high *Pr*.

1. Introduction

Natural convection, also termed as buoyancy induced flow plays a vital role in various engineering, industrial and natural applications. Typical applications of natural convection include solar ponds [1], geothermal plants and heat exchangers [2], fuel cells [3], processing of electronic equipments [4], melting process [5,6], food processing [7,8], crystal growth [9], cooling process [10] etc. Investigation of natural convection within confined enclosures (internal natural convection) are particularly complex where both heat and fluid flow distributions are highly influenced by various process and geometrical parameters. Analysis of internal flow problems lead to complex physics due to coupling between the momentum and thermal transport properties. Also, the heat and fluid flow distributions are dependent on the complexity of solid boundaries of the enclosure. The problem of natural convection becomes further complicated when the flow is considered in an enclosure with complicated geometrical configuration.

The shapes and geometrical configurations of enclosed cavities play a vital role in various applications such as thermal processing of materials. Enclosures with flat solid walls (square, rectangular, trapezoidal, triangular, etc.) are the most common types of geometrical configuration as reported by various researchers [11–16]. Experimental investigation for laminar natural convection for air in square cavity with a partition on the top wall is carried out by Wu and Ching [11]. In another work, Basak et al. [12] performed numerical simulation of natural convection and examined the effect of temperature boundary conditions on heat transfer characteristics in a square cavity. Saravanan and Sivaraj [13] analyzed natural convection in an air filled square enclosure with a localized non-uniform heat source that is mounted on the central region of the bottom wall. Study of natural convection during melting of a phase change material (PCM) in a rectangular enclosure is presented by Qarnia et al. [14]. Sieres et al. [15] carried out numerical study of laminar natural convection with and without the presence of surface-to-surface radiation within right-angled triangular cavities filled with air. Investigation of several physical

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Nomenclature

g	acceleration due to gravity, m s^{-2}
L	height or length of base of the enclosure, m
L_l	dimensionless distance along left wall
L_r	dimensionless distance along right wall
N	total number of nodes
Nu	local Nusselt number
$\overline{Nu}$	average Nusselt number
p	pressure, Pa
P	dimensionless pressure
Pr	Prandtl number
R	Residual of weak form
Ra	Rayleigh number
S	dimensionless entropy generation
S_θ	dimensionless entropy generation due to heat transfer
S_ψ	dimensionless entropy generation due to fluid friction
S_{total}	dimensionless total entropy generation
s'	dummy variable
T	temperature, K
T_0	bulk temperature, K
T_h	temperature of hot right wall, K
T_c	temperature of cold left wall, K
u	x component of velocity
U	x component of dimensionless velocity
v	y component of velocity
V	y component of dimensionless velocity
x	distance along x coordinate
X	dimensionless distance along x coordinate
y	distance along y coordinate
Y	dimensionless distance along y coordinate

Greek symbols

α	thermal diffusivity, m^2 s^{-1}
β	volume expansion coefficient, K^{-1}
γ	penalty parameter
θ	dimensionless temperature
ν	kinematic viscosity, m^2 s^{-1}
ρ	density, kg m^{-3}
Φ	basis functions
ϕ	irreversibility distribution ratio
φ	angle made by the tangent of curved wall with positive X axis
ψ	dimensionless streamfunction
Ω	two dimensional domain
ξ	horizontal coordinate in a unit square
η	vertical coordinate in a unit square

Subscripts

k	node number
l	left wall
r	right wall

and geometric parameters for natural convection in trapezoidal cavities with two internal baffles was carried out numerically by da Silva et al. [16] using the element based finite volume method.

Although analysis of natural convection in simple enclosures has been the topic of great interest, but many industrial or process applications involve cavities with irregular shapes where complexity of walls influences the characteristics of flow and heat transfer rates which are often far from being simple. A few recent studies on natural convection within enclosures with curved/wavy walls were reported by earlier researchers [17–22]. Although significant number of research works on internal natural convection in enclosures with complicated geometries appear in literature [17–22], but analysis with energy efficient approach is yet to appear and current work is an attempt on analysis of natural convective heat transfer within complex cavities via energy efficient approach for thermal engineering applications.

The thermal efficiency of a system can be assessed based on the laws of thermodynamics, but all the above mentioned works are based on first law of thermodynamics. An efficient system may be defined based on minimization of exergy loss or loss due to irreversibilities for flow and heat transport. The irreversibilities are quantified based on second law of thermodynamics via analysis of entropy generation. The quantity "exergy" represents the "useful energy" of a system and the destroyed exergy or exergy loss is proportional to the entropy generation. During natural convection, the entropy generation or exergy loss in thermal processing should be minimized to achieve an optimal processing situation with minimum irreversibilities. The optimum condition can be assessed via entropy generation minimization (EGM). Comprehensive discussion on analysis of entropy generation for various physical systems with many practical and engineering applications was provided by Bejan [23–26]. A few earlier works on entropy generation during natural convection within enclosures with various geometries are reported in the literature and are discussed briefly next.

A few studies based on entropy generation during natural convection within square or rectangular cavities with various thermal and process parameters have been reported in the literature [27–31]. Numerical investigation on entropy generation during natural convection in vertical channel for symmetrically and uniformly heated wall was carried out by Andreozzi et al. [27]. The influence of Rayleigh number and irreversibility distribution ratio heat transfer and fluid friction irreversibility during natural convection within square cavities is examined numerically by Magherbi et al. [28]. Erbay et al. [29] performed a computational study to access entropy generation for transient laminar natural convection in a square cavity in presence of completely or partially hot left wall and cold right wall. Analysis of buoyancy driven convection via entropy generation was carried out for Γ-shaped enclosures by Dagtekin et al. [30]. In another study, Famouri and Hooman [31] investigated the entropy generation during free convection in a partitioned square cavity, with adiabatic horizontal and isothermally cold vertical walls. They concluded that fluid friction irreversibility has very less contribution to total entropy generation and heat transfer irreversibility increases with dimensionless temperature difference and Nusselt number. In addition, researchers also worked on entropy generation for natural convection in triangular enclosures and inclined enclosures [32–35]. Entropy generation during natural convection within non-uniformly heated porous isosceles triangular cavities with various positions was studied by Varol et al. [32]. Recently, analysis of entropy generation during natural convection in a porous right angled triangular enclosure is carried out by Basak et al. [33]. Baytas [34,35] analyzed thermodynamic optimization and entropy generation during natural convection in inclined enclosures filled with fluid or porous media. Also, an extensive review of second law analysis of thermodynamics in enclosures due to natural and mixed convection flow for energy systems was performed by Oztop and Al-Salem [36].

Most of the earlier investigations of entropy generation during natural convection are concerned on the heat transfer in enclosures with flat wall. As reported in the literature, a few recent investigations were focused on the natural convection and entropy generation in enclosures with more complex geometric configurations