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Role of differential vs Rayleigh-Bénard heating at curved walls for efficient processing via entropy generation approach

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ABSTRACT

The present study deals with the finite element based numerical simulations of heat transfer and entropy generation rates during natural convection for fluid saturated porous media in enclosures involving curved walls (case 1: lower curvature and case 2: higher curvature) with various thermal boundary conditions. The differential heating (isothermally hot left wall and cold right wall and adiabatic horizontal walls) and Rayleigh-Bénard heating (isothermally hot bottom wall and cold top wall involving adiabatic left and right walls) are considered. The locations and magnitudes of the entropy generation due to heat transfer (S_θ) and fluid friction (S_ψ) are presented and discussed based on the spatial distributions of isotherms and streamlines, respectively. The magnitudes of local entropy generation (S_θ, S_ψ), total entropy generation (S_{total}) and average heat transfer rates ($\overline{Nu_r}$ and $\overline{Nu_t}$) are significantly lesser for the Rayleigh-Bénard heating compared to the differential heating for all the cases involving all Da_m and Pr_m. The Rayleigh-Bénard heating is the optimal strategy for all Da_m and Pr_m involving both the concave cases except for $10^{-3} \leqslant Da_m \leqslant 10^{-2}, Pr_m = 10$ and case 1 (concave) domain. The Rayleigh-Bénard heating is also the optimal strategy compared to the differential heating involving the convex cases at $10^{-5} \leqslant Da_m \leqslant 10^{-4}$ whereas the differential heating is the optimal heating strategy for $Da_m \geqslant 10^{-3}$ involving both Pr_m for the convex cases.

1. Introduction

Natural convection in enclosed cavities (internal natural convection) is one of the self sustained areas of research in the heat transfer community based on various industrially and practically important applications. Typical examples include thermal energy storage systems [1–3], melting and solidification processes [4–7], vapor absorption [8], electronic packaging [9], battery thermal management [10], fuel cells [11] etc. In particular, a significant effort has been devoted to study the convective transport within enclosures involving various geometrical shapes [12–17].

Based on the earlier works, the flow structures and temperature distributions are extremely sensitive to the shape of the walls and geometrical orientation of the enclosure during natural convection. During the conventional industrial and practical applications, the geometrical shape of the walls of the cavity/enclosure plays the pivotal role and the shapes are far from being simple. Thus, in addition to the study of natural convection involving simple geometries [12–17], the study of natural convection within enclosures involving complicated geometries with wavy or curved walls has been an important subject of research. A number of earlier works have showed the importance of the complicated geometries on the trends of heat and fluid flow characteristics during natural convection in porous media [18–27]. It was concluded from the earlier works [18–27] that, the presence of the wavy or curved walls results in the significant variation of the temperature distribution and fluid flow characteristics. In addition to the geometrical shape of the enclosure, the imposed thermal boundary conditions also influence the temperature distributions and flow structures.

All processes are inherently irreversible. Thus, the associated heat transfer and fluid flow processes during natural convection are irreversible leading to the entropy generation. The entropy generation leads to the destruction of the useful energy in the system and that can be quantified via the second law of Thermodynamics. Based on the second law of Thermodynamics, the optimal criteria depend on the minimization of the entropy generation encountered in fluid flow and heat transfer processes. The method of optimization based on the second law of Thermodynamics is termed as the entropy generation minimization (EGM). The detailed discussions on the fundamental concepts of EGM were addressed by Bejan [28]. Comprehensive reviews on the studies of the entropy generation in convective processes within enclo-

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Nomenclature

Da_m	Darcy number
G_h	gain in heat transfer rate
g	acceleration due to gravity, m s^{-2}
L	length of the base or side walls, m
$\mathbf{n}$	normal vector in outward direction
Nu	local Nusselt number
$\overline{Nu}$	average Nusselt number
p	pressure, Pa
P	dimensionless pressure
Pr_m	Prandtl number
R	residual of weak form
Ra_m	Rayleigh number
S	length of the curved wall
S_e	saving in the entropy generation rate
s'	dimensionless distance along the curved wall
T	temperature, K
T_h	temperature of hot wall, K
T_c	temperature of cold wall, K
u	x component of velocity, m s^{-1}
U	x component of dimensionless velocity
v	y component of velocity, m s^{-1}
V	y component of dimensionless velocity
x	distance along x coordinate, m
X	dimensionless distance along x coordinate
y	distance along y coordinate, m
Y	dimensionless distance along y coordinate

Greek symbols

α	thermal diffusivity, m^2 s^{-1}
β	volume expansion coefficient, K^{-1}
ϵ	porosity of the porous matrix
γ	penalty parameter
θ	dimensionless temperature
ν	kinematic viscosity, m^2 s^{-1}
ρ	density, kg m^{-3}
Φ	basis functions
Π	dimensionless heatfunction
φ	angle made by 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
b	bottom wall
l	left wall
r	right wall
t	top wall
s	surface/wall
m	modified parameters

Superscripts

e	element number

sures for various energy systems and applications are also presented in the literature [29,30].

The classical thermal boundary conditions as imposed by the earlier researchers are the differential (finite temperature difference between the left and right walls involving adiabatic horizontal walls) and Rayleigh-Bénard heating (finite temperature difference between the top and bottom walls involving adiabatic side walls) situations. A few earlier works are based on the entropy generation during natural convection within enclosures with flat or curved walls in the presence of the differential or Rayleigh-Bénard heating involving fluid and porous media [31–40].

The current work aims to understand the flow and thermal characteristics within cavities with curved walls which are useful for various processing industries. The two heating strategies such as differential and Rayleigh-Bénard are considered as case studies. The straight opposite walls are considered as adiabatic whereas other opposite pair (concave or convex) is maintained isothermally hot and cold. Identical heat input within specific cavities with curved isothermal walls (concave or convex) has been considered and the efficacy of the heating strategy has been established via two factors: reduction of the entropy generation and enhancement of the heat transfer rate at the cold wall. An efficient process is accompanied by the reduced entropy generation with the enhanced heat transfer rate. Either the differential or Rayleigh-Bénard heating can correspond to reduced entropy generation with high heat transfer rates. The proposed study deals with the detailed analysis of flow and thermal characteristics associated with the spatial entropy generation distributions. Based on the complexity of the enclosure walls, the trends of the temperature distribution and flow characteristics may result in the interesting patterns and the analysis of the entropy generation may be used for the guideline on the selection of the heating strategy. The overall entropy generation vs heat transfer rate finally decides that either differential or Rayleigh-Bénard heating strategy is efficient for a cavity with concave or convex walls with low or high curvatures. In this context, the extensive comparative study of the differential and Rayleigh-Bénard heating strategies is carried out as a first attempt in the current work for natural convection within cavities with curved (concave/convex) walls.

The current work deals with natural convection within porous cavities with curved (convex/concave) side (left and right) or horizontal (top and bottom) walls. Two classical thermal boundary conditions are employed: (a) differential heating involving the hot left wall and cold right wall in the presence of the insulated horizontal walls and (b) Rayleigh-Bénard heating involving the hot bottom wall and cold top wall in the presence of the insulated side walls. The study is carried out for the enclosures with the concave (case 1: less concavity and case 2: high concavity) and convex (case 1: less convexity and case 2: high convexity) side or horizontal walls involving various fluids with different modified Prandtl numbers ($Pr_m = 0.025$: molten metal, and 10: saline water) for a range of modified Darcy numbers ($Da_m = 10^{-5} - 10^{-2}$) at a high value of modified Rayleigh number ($Ra_m = 10^6$). The non-linear coupled partial differential equations governing the heat and fluid flow fields are solved via the Galerkin finite element method with the penalty parameter to obtain the velocity (U and V) and temperature (θ) components. The finite element basis sets are also used to calculate the Nusselt numbers and entropy generation rates. The numerical results are presented in terms of the spatial illustrations of the isotherms (θ), streamlines (ψ) and entropy generation due to heat transfer and fluid friction (S_θ and S_ψ) involving various test cases. The total entropy generation rate (S_{total}), average Bejan number (Be_{av}) and average Nusselt number ($\overline{Nu_r}$ and $\overline{Nu_t}$) are illustrated for various test cases at different Da_m and Pr_m. The optimal heating