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Natural convection in rhombic enclosures with isothermally heated side or bottom wall: Entropy generation analysis

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HIGHLIGHTS

- Energy efficient convection systems can be designed by reducing irreversibilities.
- Rhombic enclosures with differential and Rayleigh–Benard heating situations are chosen.
- Heat transfer (S_θ) and fluid friction irreversibilities (S_ψ) have been reported.
- Heating patterns and geometrical orientations have been analyzed based on entropy generation.
- Appropriate rhombic angles (φ) have been proposed based on irreversibility analysis.

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ABSTRACT

The energy efficient convection systems can be designed by reducing exergy losses. In this context, the analysis on the entropy generation during natural convection in the fluid-filled (Prandtl number, $Pr = 0.015 - 1000$) rhombic enclosures with various inclination angles (φ) has been carried out for the efficient thermal processing in various applications such as the chemical reactor modeling, underground coal gasification, and nuclear reactors. The enclosure is subjected to the differential heating (case 1) and Rayleigh–Benard convection (case 2). The conduction based static solution occurs only for $\varphi = 90°$ and it is observed that the conduction based static solution disappears with a slight perturbation of φ at Rayleigh number, $Ra \geq 2 \times 10^3$ irrespective of Pr in case 2. The active zones of the heat transfer irreversibility (S_θ) and fluid friction irreversibility (S_ψ) are found to occur near the isothermal walls for all φs irrespective of Pr in both the cases at $Ra = 10^5$. In addition, the active zones of S_ψ are also found to occur near the adiabatic walls of the cavity for all φs irrespective of Pr in both the cases at $Ra = 10^5$. Also, the region between the fluid layers of primary circulation cells acts as the strong active zone of S_ψ for all φs in case 2 at lower Pr ($Pr = 0.015$) and $Ra = 10^5$. The total entropy generation (S_{total}) and maximum heat transfer rates ($\overline{Nu}$) are found to be significantly low for $\varphi = 30°$ in both the cases at $Ra = 10^5$ irrespective of Pr. Analysis of heating patterns and geometrical orientations relates the exergy to irreversibilities which establishes that the rhombic cavity ($\varphi = 30°$) with the differential heating pattern may be the optimal design based on the energy efficient perspective.

1. Introduction

The thermodynamic efficiency of any irreversible process has to be calculated based on the reversible process as a reference scale according to second law of thermodynamics instead of the energy balance of a particular irreversible process according to the first law of thermodynamics. As the heat transfer processes involving natural convection are inevitable in most of the industrial (i.e. electronic cooling) and natural processes (i.e. building insulation) [1–7], the increase in the thermodynamic efficiency of the heat transfer processes is of vital importance to conserve the heat energy. The increase in the thermodynamic efficiency of the heat transfer processes can be done either by increasing the minimum heat input or by utilizing existing heat energy in more appropriate manner. The former approach is usually not preferred in many engineering and natural applications, because it needs an additional energy requirement or thermal system dimensions.

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Nomenclature

Be	Bejan number
f	Function
g	Acceleration due to gravity, m s^{-2}
k	Thermal conductivity, W m^{-1} K^{-1}
L	Side of the rhombic cavity, (m)
N	Total number of nodes
n	Normal vector to the plane
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 due to heat transfer and fluid friction
T	Temperature of the fluid, K
T_o	Bulk 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	Dimensionless distance along x coordinate
x	Distance along x coordinate, m
Y	dimensionless distance along y coordinate
y	Distance along y coordinate, m

Greek symbols

α	Thermal diffusivity, m^2 s^{-1}
β	Volume expansion coefficient, K^{-1}
γ	Penalty parameter
θ	Dimensionless temperature
μ	Dynamic viscosity, kg m^{-1} s^{-1}
ν	Kinematic viscosity, m^2 s^{-1}
ρ	Density, kg m^{-3}
ϕ	Irreversibility distribution ratio
φ	Inclination angle with the positive direction of X axis
Φ	Basis functions
ψ	Dimensionless streamfunction
Ω	Two dimensional domain

Subscripts

i	Global node number
k	Local node number
b	Bottom wall
l	Left wall
r	Right wall
s	Side wall
av	Spatial average
$total$	Summation over the domain

Superscripts

e	Element

Therefore, the second option is more convenient to apply, but it is constrained by the irreversibilities of the conventional heat transfer processes (i.e. heat transfer, fluid friction, etc.). The heat flow visualization on natural convection in rhombic enclosures with the isothermal hot side or bottom wall has been addressed in an earlier article [8] (to be referred as part 1) while current work attempts to quantify the generation of irreversibilities (entropy) during natural convection in rhombic enclosures with the isothermal hot side or bottom wall.

The heat transfer and fluid friction irreversibilities are measured in terms of the entropy generation based on second law of thermodynamics. Applying the new methodology termed as *Exergy Analysis* and its optimization tool via *Entropy Generation Minimization* (EGM) proposed by Bejan [9–11] in heat transfer applications, the energy destruction can be easily identified to meet the requirement of energy efficient heat transfer processes. 'Exergy' quantitatively represents 'useful energy'. By accounting all the exergy streams of the system, it is possible to determine the extent of exergy destruction. This deviation of the destroyed exergy is proportional to the entropy generation which is further responsible for the poor thermal efficiency of the system.

In recent years, there is a large volume of the literature in the concept of the efficient energy transfer systems based on the entropy generation analysis for various applications and the application categories may be based on cavities of different geometrical configurations, cavities filled with different fluids, etc. The prediction of irreversibilities (entropy active zones) during natural convection is important to improve the thermodynamic efficiency of the heat transfer processes. The precise and accurate knowledge about flow and heat transfer characteristics during natural convection is needed to model and mathematically predict active zones of the entropy generation. The accurate evaluation of derivatives is the key issue for the estimation of irreversibilities as the small error in the calculation of temperature and velocity gradients would lead to the irreversibilities with larger errors since the derivatives are powered to 2 in the entropy generation equation. In recent past, the significant amount of works have been reported on the entropy generation analysis for various physical situations [12–18] due to its importance in enhancing the thermal design of the system. Many studies on the analysis of the entropy generation for enclosures with various shapes involving square/non-square enclosures have been reported in the literature. A brief review on the entropy generation for buoyancy-induced flows in the cavity and channels is presented by Oztop and Al-Salem [19].

Numerical simulations conducted by Saleem et al. [20] to study the influence of thermocapillary forces on natural convection of a Newtonian fluid contained in an open cavity revealed the fact that the active spot of the maximum entropy generation depends on the magnitudes of Grashof number, Prandtl number and Marangoni number. Natural convection of the laminar air flow in the Gamma-shaped enclosure with circular corners was investigated by Ziapour and Dehnavi [21] using the finite-volume method and it is reported that Bejan number increases with the decrease in the irreversibility ratio in the cases of the large radius corners. The entropy generation in natural convection through an inclined rectangular cavity was numerically calculated by Bouabid et al. [22] using the Control Volume Finite Element Method (CVFEM). They found that the structure of the flows inside the cavity depends on four dimensionless parameters such as thermal Grashof number, the inclination angle, the irreversibility distribution ratio and the aspect ratio of the cavity. Further, the effect of the magnetic field on the entropy generation with the thermosolutal convection [23] and the discrete heater at the vertical wall of the cavity [24] is also reported. Current work focuses on the analysis of the entropy generation during natural convection in rhombic enclosures based on inclination angles to meet the requirement of various industrial applications involving the electronic cooling, solar heating, etc.