ABSTRACT

In modern times, thermal systems in the form of enclosures or cavities are widely used in various applications. As the demand for energy-efficient miniature devices continues to grow, passive cooling systems operated by natural convection have become a popular choice. However, the heat transport physics in these systems is significantly affected by various factors such as geometry, boundary conditions, and multi-physical processing parameters. Therefore, thermal management is critical, especially in designing thermal systems involving higher performance, miniaturization, and passive cooling methods.

Passive cooling systems relying on natural convection have emerged as a viable solution for efficient heat dissipation in various applications. For instance, designing electronic devices with higher performance and miniaturization requires effective thermal management. However, understanding the heat transport physics in these systems requires taking into account various factors, such as geometry, boundary conditions, and processing parameters. The buoyancy-induced flow in enclosures is diverse and multidisciplinary, encompassing fluid mechanics, heat transfer, and materials science.

Although there is a vast amount of literature available on convective thermal systems, none of them has thoroughly examined the impact of geometrical shape. For the past few decades, researchers have been striving to develop energy-efficient thermal devices, which have led to numerous studies on passive cooling applications utilizing buoyancy-driven flow. However, despite the abundance of literature on buoyancy-driven flow in thermal systems, there is a noticeable gap in research on constraint-based thermal analysis.

This current work presents a novel approach to constraint-based thermal analysis, which is applied to analyze the heat transfer characteristics of various-shaped enclosures. The objective is to develop a methodology for comparative performance analysis of thermal systems involving different geometries for buoyancy-driven flow in enclosures, considering recent advancements such as nanofluid and magneto-hydrodynamics (MHD). The present study aims to identify the most efficient geometric shape from a thermal performance viewpoint while using the same heat input and working fluid volume. To assess thermodynamic irreversibility in thermal systems, the entropy generation for MHD nanofluidic convection is

evaluated. The entire work focuses on heat transport, fluid flow, heat transfer, and irreversibility production during MHD nanofluid flow in the constraint-based analogous square, trapezoidal, triangular, and annular thermal systems. Annular systems have been extensively researched in terms of their application in heat-exchanging devices, particularly buoyancy-driven convection.

The study focuses on typical regular geometric shapes such as square, circular, trapezoidal, and triangular geometries, along with square and circular annuli. To evaluate the performance of various enclosure-shaped thermal systems, the square-shaped configurations have been selected as the base cases. Classical differential heating configurations are chosen for this constraint-based performance analysis of the chosen problems. The study also considers the effect of magnetic fields and nanofluids on buoyancy-driven flow. The practical working fluids used in the study are air, water, and CuO-water nanofluid. The formulated problems for this study include buoyant flow in (1) equivalent square and circular thermal systems, (2) MHD flow in equivalent square and circular thermal systems, (3) MHD flow in equivalent square and trapezoidal thermal systems, (4) MHD flow in equivalent square and triangular thermal systems, and (5) MHD flow in equivalent square and circular annular thermal systems. For the trapezoidal case, a series of several trapezoidal-shaped systems of identical fluid volume and heating load however varying cooling surfaces are investigated, and the triangular–shaped system is treated as a special case of a trapezoidal-shaped system where one parallel length approaches zero. Two cases of alternative circular annuli are analyzed against the performance of a base square annulus.

In this study, the flow is assumed laminar, steady, incompressible, and two-dimensional, and the Boussinesq approximation. The fluid and heat flow describing governing equations are solved numerically using a Computational Fluid Dynamics (CFD) tool, and local and global performance parameters are computed from the solved variables. The Nusselt number is used to measure the rate of heat transfer, and entropy generation is considered to identify the efficacious thermal system. The study focuses on the effects of Rayleigh number (Ra), Hartmann number (Ha), magnetic field angle, and nanofluid concentration on the thermal performance of various thermal systems. The Rayleigh number quantifies the ratio of buoyancy and viscosity forces, while the Hartmann number represents the ratio of electromagnetic forces to

viscous forces. These dimensionless numbers play an essential role in the heat transport physics of buoyancy-driven flow.

Following the same set of governing equations and numerical approach, the afore-stated five problems are analyzed, by comparing with the base case, using the local flow features (streamlines, isotherms, heatlines, and entropy generation contours), and global performance parameters (maximum magnitudes of streamfunction and heatfunction, heat transfer performance parameter, and the average Nusselt number). The findings of this study provide insights into the thermal behavior of various-shaped enclosures under buoyancy-driven flow conditions. The analysis shows that the circular-, trapezoidal-, and triangular-shaped enclosures offer superior thermal performance compared to the traditional square-shaped enclosure. The circular annular thermal system also shows better thermal performance than its equivalent square annular system. Obtained results are explained from the fundamental physics. Each problem is devoted to a chapter for the systematic presentation of various parametric results exploring the effects of Rayleigh number (Ra), Hartmann number (Ha), magnetic field angle, and nanofluid concentration.

In conclusion, the present study proposes a constraint-based methodology for comparative performance analysis of various-shaped thermal enclosures under buoyancy-driven flow conditions. The study includes the effects of magnetic fields and nanofluids on heat transfer and irreversibility production in thermal systems. The findings provide insights into the thermal behavior of various-shaped enclosures and identify the most efficient geometric shape from a thermal performance viewpoint. The results can be applied to a wide range of engineering and industrial applications, from the design of cooling systems in electronics to the optimization of energy systems.