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Natural Convection in a Square Enclosure with Embedded objects through Magnetic Field

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ABSTRACT: This work investigates magneto-hydrodynamic (MHD) conjugate natural convection and entropy formation in a nanofluid-filled square enclosure with several heat-generating devices under Joule heating. The numerical study employs a finite element method to solve the governing mass, momentum, and energy equations, revealing the intricate interplay between thermal and fluid dynamic behaviors. Key factors such as the Rayleigh number (Ra), Hartmann number (Ha), nanoparticle volume fraction, and Joule heating parameter are systematically adjusted to determine their effect on heat transport and entropy formation.

The study looks into two different configurations of heat-generating devices, each with its own spatial arrangement, with the goal of improving thermal performance. Under certain operating conditions, pure water as the base fluid outperforms nanofluids in terms of heat transfer efficiency. However, nanofluids have better thermal conductivity, which can be useful in high Rayleigh number regimes. Furthermore, the study emphasizes the importance of the enclosure's inclination angle for heat management. An angled arrangement alters convective flow patterns, which affects heat dissipation and energy efficiency.

The entropy generation analysis highlights the trade-off between thermal enhancement and enhanced viscous dissipation caused by nanoparticles. The magnetic field's stabilizing action lowers flow instability, which further optimizes the thermal system. These insights are crucial for building advanced thermal systems used in electronic cooling, nuclear reactors, and renewable energy systems. The report provides useful advice for strategically placing heat sources and effectively utilizing MHD effects to improve overall system performance.

KEYWORDS: Magneto-hydrodynamic(MHD), natural convection, Nanofluids, Rayleigh number (Ra), Heat transfer, Heat-generating devices, Thermal conductivity Energy efficiency, Finite element method.

I. INTRODUCTION

Temperature gradients produce natural convection, which is important in many technical applications, including electronic cooling, solar energy systems, and nuclear reactor control. This type of convection occurs when buoyant forces caused by temperature-induced density differences drive fluid flow, allowing heat to be transferred from high-temperature regions to cooler ones. It is an important mechanism in the design of heat exchangers, thermal storage systems, and other industrial cooling systems.

The combination of magneto-hydrodynamic (MHD) effects and nanofluids improves thermal management by leveraging distinct qualities such as enhanced thermal conductivity, increased specific surface area, and improved suspension stability. MHD is the study of magnetic effects on electrically conducting fluids, in which an applied magnetic field affects fluid flow and heat transfer by generating a Lorentz force. This phenomena is especially useful for controlling fluid motion in hot systems where traditional approaches may be ineffective, such as high-power electronic devices or nuclear reactors. Previous research have shown that nanofluids can improve heat transfer rates, especially in applications that require great thermal efficiency. Nanoparticles like TiO_2, Al_2O_3, or Cu improve heat conduction in base fluids like water or oil, resulting in greater convective heat transfer and reduced thermal resistance. These improvements make nanofluids excellent candidates for cooling systems in microelectronics, automobile engines, and even biomedical applications. The combination of MHD effects and nanofluids, in particular, brings up new possibilities for improving thermal performance in enclosures with heat-generating devices. Magnetic fields used to nanofluids in these systems can control flow dynamics, reduce turbulence, and improve heat transfer stability. The

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interplay of the applied magnetic field and thermally induced fluid motion causes a more uniform temperature distribution within the enclosure, which improves heat dissipation and reduces hotspots. This combination approach has the potential to transform thermal management systems, particularly in conditions where both heat generation and fluid movement must be precisely managed for optimal performance.

Fig.1 This creates buoyancy-induced convection currents in the nanofluid because the heat-generation elements cause localized thermal gradients. The introduction of δ in the enclosure introduces an extra parameter to the flow dynamics and the heat transfer characteristics. This is the relevant configuration for studying the influence of magnetic fields, heat generation, and inclination angle on convective heat transfer and entropy generation. The goal of the setup is the optimization of thermal performance and fluid flow stability in advanced thermal management systems.

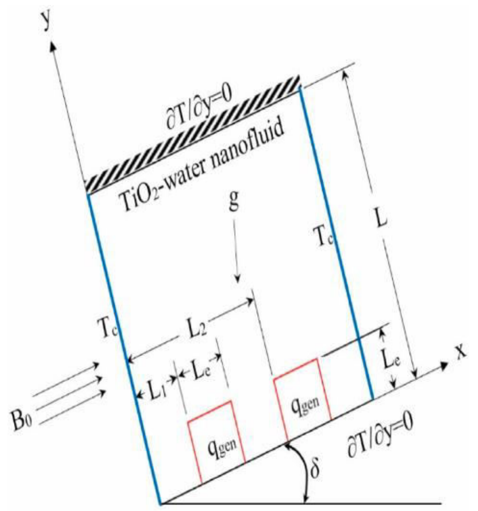

Fig. 1. Schematic diagram of the square enclosure having two heat-generating solid elements along with boundary conditions in the Cartesian coordinate system.

II. NATURAL CONVECTION

Natural convection, a phenomenon where fluid motion is driven by buoyancy forces arising from temperature gradients, plays a crucial role in systems where heat transfer is essential. In a square enclosure with embedded objects under the influence of a magnetic field, the dynamics of natural convection become more complex due to the interplay of thermal, fluid flow, and electromagnetic forces. Lorentz forces are the mechanism of influence between the magnetic field and conducting fluid, suppressing or otherwise modifying fluid motion in large effect on convection patterns. This suppression is highly effective at higher Hartmann numbers, where magnetic forces tend to dampen the buoyancy driven motion of the fluid while decreasing the efficiency of the convective heat transfer mechanism.

The presence of embedded objects, such as cylinders or fins, brings added complexities by causing disruption to the flow and producing localized recirculation and thermal gradients. They act as sources or sinks of heat, which in turn affect the temperature distribution and heat transfer performance within the enclosure. The shape, size, and thermal properties of such embedded objects are important factors determining convection dynamics. For example, obstacles of higher thermal conductivity promote enhanced heat dissipation, but their arrangement may either contribute to or hinder convective currents.

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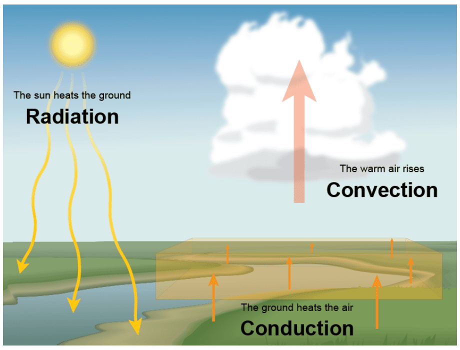

Fig.2 Natural convection

A Rayleigh number, Ra, characterizes the dominance of buoyancy forces over viscous forces and determines the strength of natural convection. The governing of conduction over viscous forces is low, but vigorous convection currents form, giving potential chaotic or turbulent flow, for high Ra values. Thus, the interplay between Ra and Ha dictates a transition between the two dominating regimes.

More specifically, the angle of inclination from which the enclosure is made greatly modifies the flow structure. Gravity now aligns with one or more temperature gradients under oblique orientation, modifying not only the strength but the direction of convective current generated as well. Such aspects prove significant in practical applications such as requiring control over heat fluxes.

In MHD systems, nanofluids are often used to augment thermal performance. Nanofluids are engineered suspensions of nanoparticles in base fluids, and their higher thermal conductivity improves heat transfer rates, however their inclusion increases viscous dissipation and entropy generation: hence, a balance needs to be struck between thermal efficiency and irreversibility.

Natural convection in such enclosures has diverse applications such as electronic cooling, energy-efficient building systems, nuclear reactor heat management, and magnetic refrigeration. Understanding and optimizing the combined effects of embedded objects, magnetic fields, and fluid properties are critical for designing advanced thermal management systems.

III. METHODOLOGY

The mass, momentum, and energy equations that are known to govern the flow and temperature fields within an enclosure are solved using FEM. FEM is a powerful numerical approach, where the governing partial differential equations are converted into a collection of algebraic equations that may be solved iteratively. This approach particularly works very well with complex geometries and boundary conditions, hence it is perfect for conjugate heat transfer simulation of fluid and solid regions involving sources of heat. Investigating the effects of MHD forces on heat transport and the formation of entropy within the nanofluid contained in a square enclosure due to the presence of an internal heat generation mechanism has been the primary purpose behind this research. It presents two configurations of internal heating devices: Configuration A - symmetrically arranged internal heat-generating devices; Configuration B - asymmetrically positioned elements. The asymmetrical arrangement in Configuration B is expected to produce a temperature gradient that improves the convective flow and heat transfer efficiency, especially at large Rayleigh numbers. These configurations have been chosen to understand the overall thermal performance of the system based on the different arrangements of heat sources. The computational domain is a square enclosure filled with TiO_2-water nanofluid. This nanofluid is extensively investigated due of its excellent thermal properties. The two heat-generating devices are embedded in the enclosure's bottom wall, and the system runs in a constant state. The enclosure's left and right vertical walls remain at a constant low temperature, while the top wall is thermally insulated to prevent heat loss. The principal heat source is the bottom surface, where the heat-generating devices are accommodated. Nanoparticle volume percentage and Joule heating are some of the critical parameters whose influence on the thermal behavior of the

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system is systematically changed. Volume fraction of nanoparticles (φ) in the nanofluid is varied to understand the influence on the rate of heat transfer. It is widely accepted that the incorporation of nanoparticles into the base fluid will enhance thermal conductivity significantly, but high volume fractions may increase fluid viscosity and low the efficiency of heat transfer. The Joule heating parameter, J, which represents the heat produced by the interaction of the magnetic field and the electric current in the fluid, is also examined in the study. Joule heating is very significant in MHD systems since it can either accelerate or impede heat transport depending on the system's parameters.

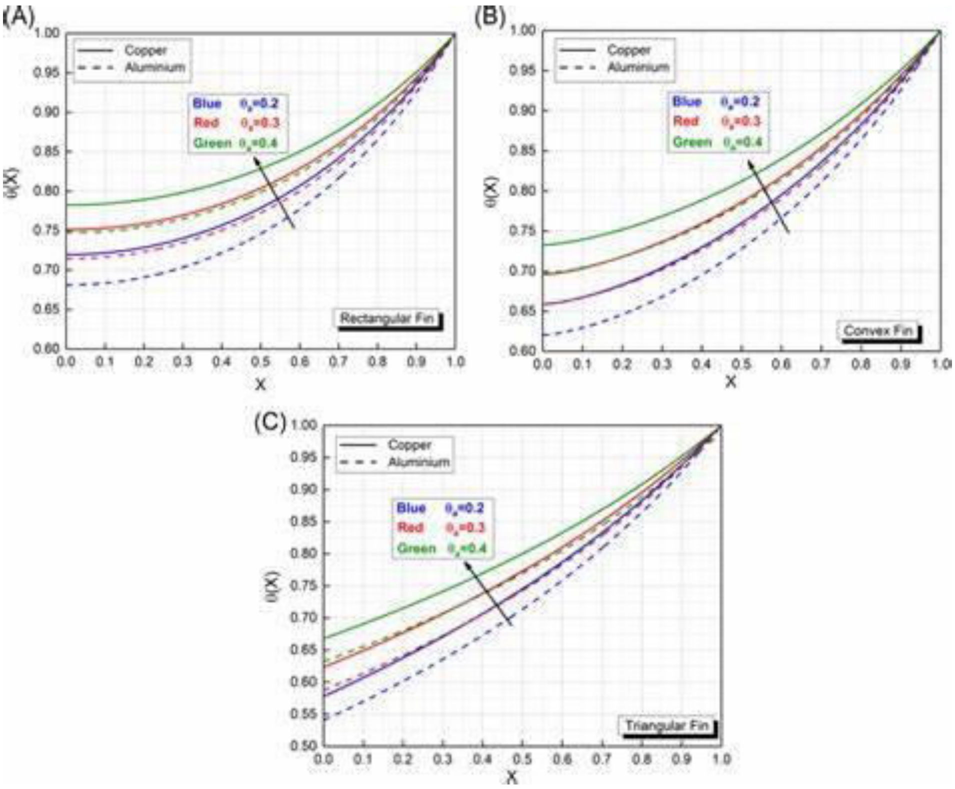

Fig.3 Performance Comparison of Copper and Aluminium Fins with Different Shapes and Nanoparticle Volume Fractions.

Fig.3 The graphs represent the performance of copper and aluminium rectangular, convex, and triangular fins with different nanoparticle volume fractions in a nanofluid. The x-axis is the normalized length of the fin (X), and the y-axis (Y(X)) is the temperature distribution along the length of the fin. Copper fins have a higher thermal performance than aluminium fins because of their better thermal conductivity. Among the fin shapes, the rectangular fins show a more uniform temperature distribution and the convex fins have slightly higher efficiency in heat dissipation with a higher surface area. Triangular fins are more compact but have a higher temperature gradient along their length, hence less effective for thermal spreading. The influence of the nanoparticle volume fraction is also observed here. This can be achieved by optimizing ϕ for both materials and geometries of the fins. The improvement in the thermal performance is due to increased nanoparticle concentration enhancing the nanofluid's thermal conductivity. The comparison presents the trade-offs that can be made between material, geometry, and nanofluid properties in maximizing heat transfer in finned thermal systems.

Furthermore, the Rayleigh (Ra) and Hartmann (Ha) values are changed across a large range to model natural convection under various buoyancy-driven and MHD conditions. The Rayleigh number describes the relative importance of buoyant forces vs viscous forces, whereas the Hartmann number shows the ratio of magnetic forces to viscous forces in the fluid. By changing these factors, the study analyzes how variations in buoyancy, magnetic field

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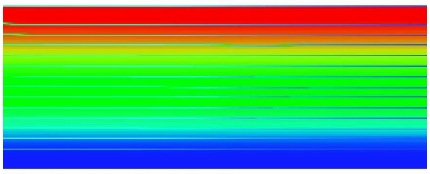
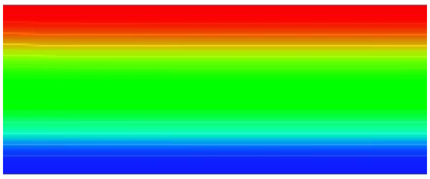
strength, and nanoparticle concentration affect flow patterns, temperature distribution, and overall thermal performance. These simulations yield useful insights into the best setup and operating conditions for optimizing thermal management systems in a variety of technical applications, including electronic cooling, solar energy collection, and industrial heat exchangers.

IV. RESULTS AND DISCUSSION

Pure water has a higher heat transfer efficiency than nanofluids, especially at lower Rayleigh numbers, according to the study. This finding shows some trade-offs in using nanofluids versus basic fluids such as water for certain purposes. Although nanofluids have been well-documented to exhibit higher thermal conductivity, the investigation found that there are conditions in which the pure water is more efficient in heat transfer compared to the nanofluids. At low Rayleigh numbers, corresponding to reduced buoyancy-driven flow regimes, it has been found that the increase in nanoparticle concentration inhibits fluid flow and results in increased viscosity, thus impeding heat transfer efficiency, particularly at low Rayleigh numbers. This phenomenon reveals that, despite the promising applications of nanofluids in high-heat flux scenarios, their efficiency can be degraded under specific flow conditions. Additionally, the distribution of heat sources is one of the most significant factors determining the system's thermal performance. If the heat-producing units are placed asymmetrically, such as in Configuration B, the convective heat transfer will be greater compared to a symmetrical arrangement. This improvement is in connection with the increased buoyancy-driven flow caused by the larger proximity of one heat-generating device towards the cold wall, wherein a steeper temperature gradient exists. The steeper gradient causes a more strengthened buoyancy effect, leading to even stronger fluid circulation and an enhanced mixing of fluids within the enclosure. Therefore, configuration B has a higher mean Nusselt number, the critical measure of heat transfer effectiveness, than configuration A, with symmetrically distributed elements. Heat transfer is also highly sensitive to the inclination degree of the enclosure. Larger tilt angles are less effective in terms of thermal performance because the gravitational forces work against buoyancy force-induced flow, which further lowers the convection coefficient. In contrast, at a 0° tilt angle, the horizontal-orientated enclosure produces the highest convective currents.



(a)



(b)

Fig.4 Streamlines showcasing the flow pattern.

Figures depicting temperature distributions and streamlining characteristics corroborate these conclusions. In Configuration A, the temperature distribution is more uniform throughout the enclosure, with a gradual temperature rise from the frigid walls to the heated surfaces. Streamline patterns imply a smoother, less turbulent flow than Configuration B. Configuration B, on the other hand, shows a more noticeable temperature gradient around the heat-generating devices, with streamlines forming strong convection cells near the heat sources. These convection cells are more vigorous, and the interaction of opposing vortices improves fluid mixing, resulting in better heat dissipation. Visualizations of isotherms (contour plots) show how temperature gradients change under various settings. In setups with greater Rayleigh numbers, the isotherms grow further spaced apart, indicating stronger buoyancy-driven flow and

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faster heat loss. The presence of nanofluids with large Rayleigh numbers raises the fluid temperature at the hot-wall contact, however the influence of nanoparticle concentration is less significant when compared to pure water in such cases. This shows that at high Rayleigh numbers, the nanoparticles' effect on thermal conductivity is dominant, whereas at lower Rayleigh numbers, their contribution to heat transmission is less significant. These representations are critical for understanding the underlying fluid dynamics and thermal patterns, allowing for a more accurate comparison of the various setups and operational situations. They shed light on the efficacy of various solutions for enhancing heat transmission and reducing energy losses caused by irreversibility in the system.

V. CONCLUSION

This study emphasizes the need of strategically placing heat-generating devices and incorporating magneto-hydrodynamic (MHD) effects to improve thermal performance in fluid-filled enclosures. The findings show that the arrangement of heat sources is essential in determining the efficiency of convective heat transfer, with asymmetric placements providing higher thermal performance. The buoyancy-driven flow has a substantial impact on the interaction between heat-generating devices and the surrounding fluid, and the employment of MHD forces, which govern flow dynamics and improve heat dissipation, amplifies this effect. The paper also underlines the need of taking into account several operational characteristics, such as nanoparticle volume percentage, Rayleigh number, Hartmann number, and Joule heating. By systematically altering these parameters, the research demonstrates that nanofluids provide substantial advantages under strong thermal gradients, but pure water may provide superior thermal efficiency at lower Rayleigh numbers. Furthermore, when combined with the magnetic field, the Joule heating parameter exhibits a complicated interaction that effects both fluid motion and thermal behavior, implying the need for parameter optimization based on individual system needs.

While the current study is based on two-dimensional simulations, it suggests various areas for further research to improve heat management systems. Future research could investigate the usage of alternative nanofluid types, such as different nanoparticle materials or hybrid nanofluids, to determine their impact on heat transfer and entropy formation under varied situations. To improve nanofluid performance, researchers could investigate the impact of nanoparticle shape, size distribution, and surface coatings on thermal conductivity and stability.

Furthermore, expanding the current study to three-dimensional configurations would provide more in-depth insights on thermal and fluid flow patterns in more realistic environments. Three-dimensional simulations may better depict the intricacies of fluid dynamics and heat transmission in enclosures with several heat-generating sources, particularly when the influence of boundary conditions is greater. Exploring transient situations, where time-dependent variations in temperature and flow occur, could also provide useful insights into the dynamic behavior of such systems and their reaction to shifting operating parameters. Furthermore, the use of advanced cooling techniques, such as phase change materials or embedded microchannel heat exchangers, could be investigated in conjunction with MHD and nanofluid systems to improve overall performance. These developments are especially important for applications such as high-speed computing, electronic cooling, and energy storage systems, where efficient thermal management is critical for system stability and performance. Overall, combining MHD effects with nanofluid-based cooling systems is a potential way to improve thermal management. This research sheds light on the complicated connections between fluid flow, heat transmission, and entropy creation in such systems, paving the way for future advances in thermal engineering.

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