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Influence of Internal Obstacle Size and Position on Magnetohydrodynamic Convection in Square Cavities

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Abstract

Understanding the impact of internal obstacle configurations on magnetohydrodynamic (MHD) convection has become essential for optimizing thermal systems such as electronic cooling devices, solar enclosures, and advanced heat exchangers. This review investigates how variations in the size and placement of internal bodies within square enclosures influence natural convection performance under the presence of magnetic fields. The paper compiles and analyzes studies from 2015 to 2024, highlighting key trends in heat transfer enhancement or suppression as a function of geometric positioning. Special focus is given to works incorporating nanofluids and different Hartmann numbers, with findings synthesized to guide future research and design improvements.

Keywords: Magnetohydrodynamics, Obstacle configuration, Thermal Performance, Cavity flow, Nanofluids, Rayleigh number, Hartmann number

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1. Introduction

Natural convection is a pivotal mode of heat transfer that results from the inherent movement of a fluid driven by internal buoyancy forces rather than external mechanical sources. This phenomenon occurs when temperature differences within a fluid cause density gradients, resulting in fluid movement. It plays an essential role in a variety of technical systems, particularly in passive thermal control applications such as electronics cooling, architectural insulation, solar thermal collectors, drying processes and thermal storage devices [1]. Its selfsufficient nature requires no external energy input, making it a favourable solution for energy efficient design. However, the complex interplay between temperature gradients, boundary conditions and geometric constraints poses considerable challenges in predicting and optimising the behaviour of natural convection.

Among the enhancements to this mechanism is the use of nanofluids, suspensions of nanoparticles within conventional base fluids, which offer superior thermal conductivity and stability. These advanced fluids have garnered significant attention for their ability to improve heat dissipation in high-performance systems, such as microelectronic devices, solar panels, and nuclear cooling loops. Their finely tuned dispersion not only mitigates the issues of sedimentation and channel blockage commonly associated with larger particles but also leads to more uniform thermal profiles and higher operational reliability [2]. Continued innovation in nanofluid formulation is expected to unlock further improvements in thermal system compactness and efficiency.

To better understand and model the impact of complex geometries on natural convection, Abdulkadhim et al. [3] surveyed a wide range of enclosures, including rectangular, elliptical, wavy, and square configurations. Their comprehensive review of numerical methods, employing key dimensionless numbers like Rayleigh, Hartmann, and Darcy, provided insight into the thermal and fluid dynamics of these geometries. Of particular interest was the similarity observed between square and diamond-shaped cavities, the latter being simply rotated forms of the former, offering design flexibility with minimal changes in flow behavior.

Complementing this, Pandey et al. [4] conducted detailed investigations, both computational and experimental, on natural convection in cavities with internal bodies, focusing on cylinders of varying shapes and orientations. The study highlighted the significance of geometrical parameters such as aspect ratio, angular positioning, and internal body placement on convective flow patterns. Employing diverse computational techniques, including finite volume and lattice

Boltzmann methods, they demonstrated how tailored internal structures could manipulate fluid flow to enhance thermal performance.

As research in this area progresses, the synergy between nanofluid science, geometric optimization, and magnetic field manipulation continues to unlock new possibilities for improving heat transfer performance. The following section presents a curated summary of recent contributions, drawing attention to key trends and findings that shape the current landscape of natural convection research.

2. The most selected parameters in the previous publications

Natural convection, a fundamental physical phenomenon, plays a critical role in numerous engineering applications, including packed layers, nuclear power system design, geological processes, electronic equipment cooling, solar collectors, heat exchangers, building ventilation systems, and other cooling systems [3].

Furthermore, the size and location of an internal body within the cavity directly impact heat flow patterns. Larger internal bodies can either enhance or diminish heat transfer efficiency, depending on their placement. Boundary conditions, such as constant or varying temperatures, and fluid properties, including viscosity and thermal conductivity, are also crucial factors influencing heat transfer dynamics. Abdulkadhim et al. [3] demonstrated that incorporating nanoparticles into base fluids, such as water, alters thermal properties and enhances heat transfer effectiveness. The positioning of heat sources significantly affects convection patterns, as evidenced by studies from Esmaeil [5] and Umadevi and Nithyadevi [6], which showed that placement near cavity edges or centrally could substantially alter heat distribution and overall system efficiency.

2.1. Conventional Square enclosure in the absence of the magnetic field

Chen et al. [7] examined heat transfer by conjugating natural convection in an open square chamber that has porous material partly filled in. They introduced a novel Lattice Boltzmann (LB) approach, validating the model through three benchmark tests: the thickness of the porous layer, the ratio of thermal conductivity between the fluid and the porous medium, and the permeability of the porous layer. The parameters for their study were set as follows: Da=10^{-3}, ε=0.6, Ra=10^{5}, σ_{Porous} = 1 and R_k=1, while the dimensionless depth-to-length ratio (d/L) varied between 0.1, 0.3, and 0.5. The findings demonstrated that the proposed model is applicable for unsteady conjugate heat transfer problems. Figure 1 illustrates the configurations at different d/L ratios, indicating the position of the pore/liquid interface. In all scenarios, fluid enters from the lower cavity and exits through the upper orifices.

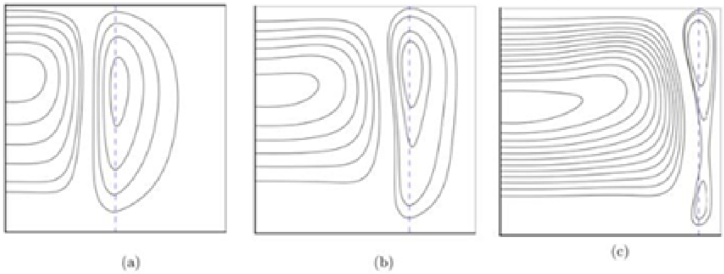


Figure 1. streamlines at the values of d/L are (a) 0.5, (b) 0.3, and (c) 0.1 [7]

Esmaeil [5] conducted a numerical investigation to explore the impact of thermophysical characteristics on laminar natural convection in a container with nanofluids that is differentially heated. This study was characterized by the Gasthof numbers Gr_f, ranging from 10 to 3 $\times 10^9$ for pure water and from 100 to 10^9 for nanofluids. The results showed that the effective thermophysical characteristics of the nanofluids were significantly changed when nanoparticles were added to the base fluid. According to a parametric analysis of the data, the viscosity of nanofluids has a significant impact on how well they transport heat. Furthermore, the viscosity of the nanofluids plays a critical role in determining their natural heat and momentum transfer properties, whereas the thermal conductivity of the nanofluids has a comparatively lesser impact.

Mehryan et al. [8] examined, using a local thermal nonequilibrium model, the conjugate natural convection of a polar nanofluid inside a porous container. To address the coupled and nonlinear equations, they employed the Galerkin finite element method. The governing parameters included the Interface parameter (H = 1–1000), porosity (ε = 0.1–0.9), and Darcy-Rayleigh number (Ra = 10–1000), relative thermal conductivity (k_r= 0.1–10), nanofluid volume fraction (φ_{nf}= 0 – 0.08), eddy viscosity parameter (Δ = 0 – 3), solid wall width (d = 0.1–0.4), and the thermal conductivity ratio between the solid wall and base fluid (R_k = 0.1–10). Their findings indicated that a slight increase in microrotational force occurred with an increase in k_r, resulting from enhanced angular momentum applied to the fluid molecules. As shown in Figure 2, the stream function value increased with H, suggesting improved thermal interaction between the matrix phases of the fluid and solid, which consequently altered the Isotherm patterns in the solid and fluid phases.

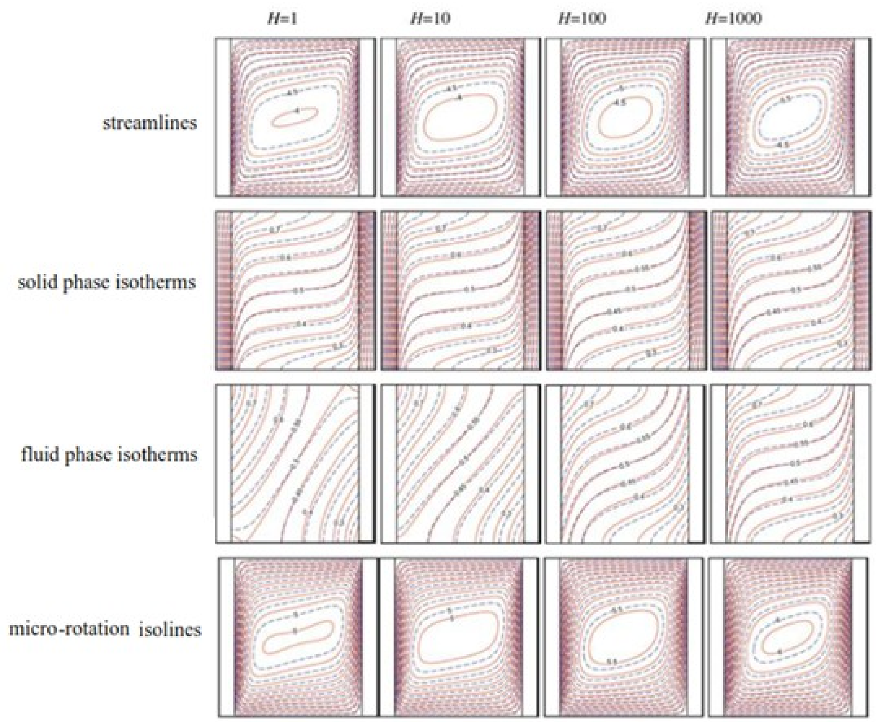


Figure 2. Dependency of streamlines, solid phase isotherms, fluid phase isotherms and micro-rotation isolines on H [8]

Reddy and Sreedevi [9] investigated the influence of thermal radiation on a nanofluid's mass transfer and natural convection heat in a square cavity, using Buongiorno's mathematical model. The study examined various parameters, including Thermophoresis number ($0.1 \leq Nt \leq 0.5$), buoyancy ratio parameter ($0.1 \leq N_r \leq 0.9$), Lewis number ($1.0 \leq Le \leq 10$), Rayleigh number ($100 \leq Ra \leq 300$), Brownian motion parameter ($0.1 \leq N_b \leq 0.9$), and radiation number ($0.1 \leq R \leq 0.9$), with results presented graphically. The findings showed that the Rayleigh number increased, an upward heat wave emerges from the left vertical heat source, while a downward heat wave forms from the right vertical heat source.

Sivarami et al. [10] examined the magnetohydrodynamic (MHD) natural convection heat transport from a heated square cylinder in a square container with uneven temperature distributions using numerical analysis. Dimensionless form was used to describe the governing equations, which were then solved using a second-order finite difference scheme using the Marker and Cell technique. In this work, the impacts of several dimensionless factors were examined, such as the eddy viscosity parameter ($0 \leq K \leq 5$), magnetic (Hartmann) parameter ($0 \leq Ha \leq 50$), and Rayleigh number ($10^3 \leq Ra \leq 10^6$). The basis fluid for all simulations was pure water, which had a Prandtl number (Pr) of 7. As shown in Figure 3, the average Nusselt number rises as the thermal Rayleigh number grows and falls as the magnetic parameter increases.

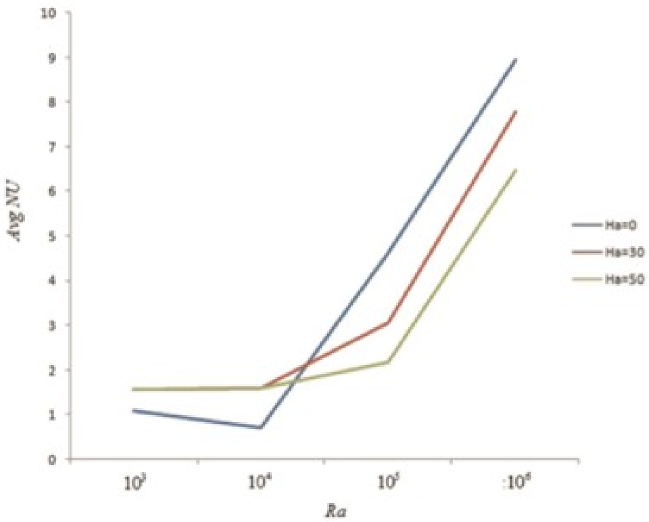


Figure 3. Average cold wall Nusselt number for various Ha values, Pr = 7, and K = 1[10]

Charreh and Saleem [11] investigated the dynamics of fluid flow, heat transfer, and entropy generation during natural convection transients in a square cavity filled with a saturated, non-porous medium, taking into account dissipation effects and thermal radiation. They employed a direct substitution method to address the boundary and initial conditions within the porous medium. The simulations were conducted across a range of relevant dimensionless parameters, including the Rayleigh number ($10^3 \leq Ra \leq 10^6$), the Gasthof number ($10^3 \leq Gr \leq 10^7$), the Eckert number ($0 \leq Ec \leq 5\times10^{-5}$), the radiation parameter ($0 \leq R_d \leq 5$), the Prandtl number ($0 \leq Pr \leq 10$), and the Chheimer resistance ($0 \leq \Gamma, \gamma \leq 10$).

2.2. Conventional Square Enclosure without Inner Body in the Presence of a Magnetic Field

El Hammami et al. [12] investigated the rate of heat transfer in a square container containing an aqueous Cu nanofluid under the influence of a magnetic field using numerical analysis. They used Maxwell's model for thermal conductivity and Brinkman's model to determine the nanofluid's effective viscosity. With a focus on examining the influence of the magnetic field at a 5% nanoparticle concentration, this study sought to forecast the impacts of the Rayleigh number, Hartmann number, and volume fraction of nanoparticles. Figure 4 displays their findings, which show the local Nusselt number along the hot wall for different Rayleigh and Hartmann values (Ha = 0, 30, and 60). The findings indicated that the magnetic field had a negligible effect on the heat transfer performance.

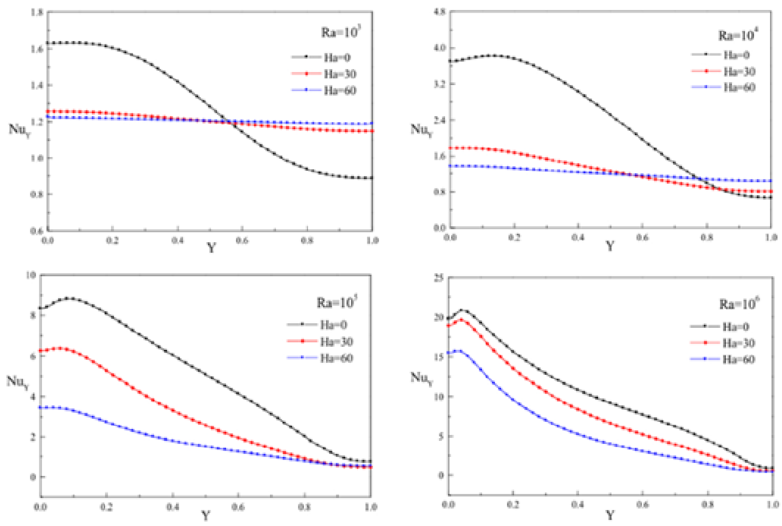


Figure 4. Local Nusselt number for different Rayleigh numbers along the cavity's left hot wall [12]

Mejri and Mahmoudi [13] conducted a comprehensive examination of natural convection in an open cavity characterized by a sinusoidal convection current. This cavity, filled with a nanofluid composed of water, was subjected to an external magnetic field. The researchers utilized the lattice Boltzmann method for numerical verification of their findings. According to their findings, the heat transfer rate and the dimensionless entropy generation number rise as the volume percentage of nanoparticles and Rayleigh number (Ra) grow, but they fall when the Hartmann number (Ha) increases. Furthermore, the study found a relationship between the volume fraction of nanoparticles and the Nusselt number (Nu). The authors investigated a broad variety of parameters, such as phase deviations (y = 0, $\pi/4$, $\pi/2$, $3\pi/4$, and π), solid volume fractions ranging from $\emptyset = 0$ to 0.06, Rayleigh numbers for the base fluid (Ra = 10^5 to 10^6), and Hartmann numbers between 0 and 60.

Another noteworthy study by Zhang et al. [14] conducted a numerical analysis of the effects of thermal radiation on Rayleigh-Magnetohydrodynamic (R-MHD) natural convection within a square cavity, examining various levels of thermal radiation. In their research, they employed the Finite Volume Method (FVM) to solve the momentum and energy equations, while utilizing the Discrete Ordinates Method (DOM) to determine the local radiant heat flux. This comprehensive approach allowed for a detailed understanding of how thermal radiation influences the flow dynamics and heat transfer characteristics in the context of R-MHD natural convection. Their findings revealed that the influence of thermal radiation on R-MHD natural convection notably decreases with increasing Pl number, while the critical Plc number drops significantly with increasing Reynolds number (Re) and rises considerably with Hartmann number (Ha). Additionally, they observed that Plc values increase with Ha, with Plc values recorded as 4.7, 4.9, 7.7, and 13.2 for Ha values of 0, 10, 50, and 100, respectively. The study highlights the crucial role of the Pl number in affecting MHD flow and temperature distribution. Figure 5 illustrates their results, showing a substantial decrease in $\overline{Nu_r}/\overline{Nu}$ at fixed Ha, indicating reduced thermal radiation effects on heat transfer, along with a notable increase in $\overline{Nu_r}$ $/\overline{Nu}$ with fixed Ha.

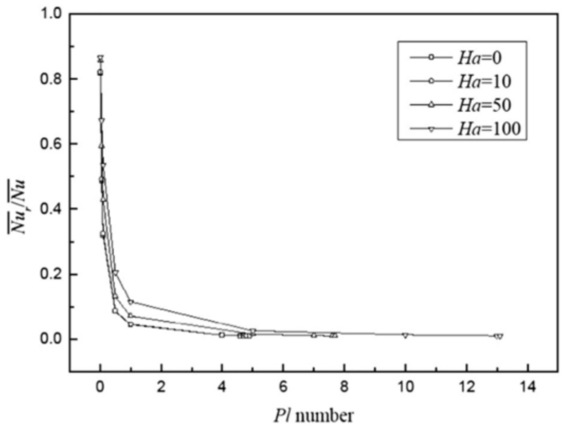


Figure 5. With Re = 500, Ri = 2, and Pr = 0.733, the ratio of Nur = Nu under various heat radiation intensities: Ha = 0 in (a), 10 in (b), 50 in (c), and 100 in (d). [14]

Bouchair et al. [15] investigated numerically how conjugate magnetohydrodynamic (MHD) natural convection in a square cavity containing an electrically conducting fluid is affected by non-uniform volumetric internal energy production. An internal software based on the Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) algorithm and the Finite Volume Method (FVM) was used to get the numerical solutions to the governing conservation equations. Their simulations, which especially examined internal Rayleigh numbers of Ra_I = 10^4, 10^5, and 10^6as well as Hartmann numbers of Ha = 0,50, and 200, showed how different controlling factors affected flow and thermal behavior. A solid-to-fluid thermal conductivity ratio of k_r = 1, a solid partition thickness of Δ = 0.2, and a cavity tilting angle of α = 0 were additional parameters. They also investigated three Prandtl number values: Pr = 0.015, 0.024, and 0.054. The outcomes provide insightful information about the complex relationships between these variables and how they affect the system's thermal performance.

Rashad et al. [16] investigated numerically the effects of heat sink, source location, and size on heat transfer, MHD natural convection, and entropy formation in a tilted porous cavity containing hydrated copper nanofluid. The dimensionless partial differential equations were solved using the finite difference technique, with constant values set at Ec = 10^{-3}, Da = 10^{-3}, Q = 1, ε = 0.5, and C_T = 0.5. Results indicate that optimal heat transfer occurs at tilt angles between 40°-50° and 300°-310° across the full range of D.

Karimdoost et al. [17] employed a straightforward algorithm to solve the governing equations for temperatures ($T_c < T_h$) and conducted simulations to assess the effects of various parameters, including Rayleigh number (Ra = 10^3 to 10^6), nanoparticle volume fraction (φ = 0 to 5%), Hartmann number (Ha = 0 to 60), and baffle length (L_1 = 0 to 0.5L). Their results demonstrated that an increase in the Rayleigh number led to enhanced flow velocity within the enclosure by elevating the temperature difference between the hot and cold surfaces.

Li et al. [18] investigated free convective heat transfer in an alumina-water nanofluid within a square cavity inclined at angle γ with respect to the horizontal. Their results revealed that both heat transfer rate (HTR) and generated entropy increased with rising Rayleigh number. Specifically, as Ra increased from 10^3 to 10^6, the HTR experienced a remarkable 4.5-fold increase. Figure 6 presents their findings on the flow field, temperature distribution, and local entropy generation at various angles, Rayleigh numbers, and aspect ratios.

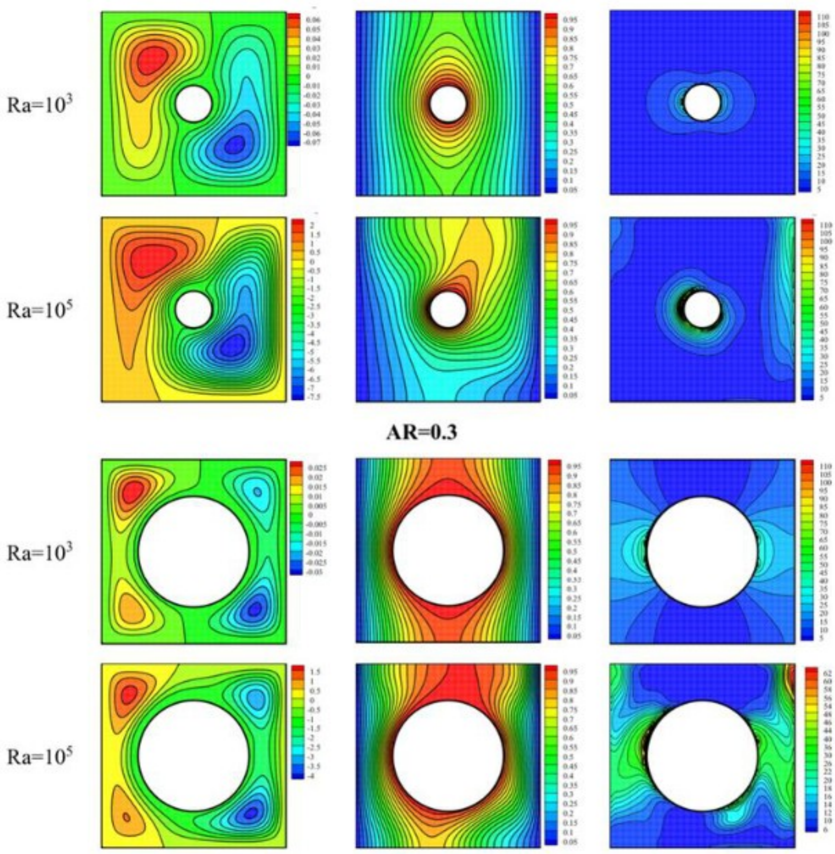


Figure 6. Temperature field, flow field and local entropy at Ha =20 [18]

Dimitrienko and Li [19] examined, using computational techniques, the natural convection heat transport of a Karo fluid in a square cavity exposed to different orientations of a uniform magnetic field. For the simulation, they used a new finite difference approach. Keeping the Prandtl number constant at 0.065, the study concentrated on parameters in the following ranges: the magnetic field inclination angle (α\alphaα) from 0 to π\piπ and the Rayleigh number (Ra) from 10^4 to 10^5. The following three fluid types were examined: Newtonian fluid (n = 1.0 or Ca = 0), shear-thickening fluid (n = 1.3, Ca = 2), and shear-thinning fluid (n = 0.7, Ca = 2). They discovered that the shear-thinning fluid's convective heat transfer and flow were more noticeable than those of the Newtonian fluid when there was no magnetic field present, while the shear-thickening fluid's convective heat transfer and flow were less noticeable than those of the Newtonian fluid.

Jino and Kumar [20] explored both constant and quadratic normal heat flow of a Cu-water nanofluid over a porous square cavity subjected to an applied magnetic field. They analyzed the governing equations that describe cavity flow patterns resulting from heated thermal wall boundaries, utilizing a cascade over-relaxation method combined with an implicit algorithm to solve the dimensionless equations. Their research discusses various parameters, these include the non-linear temperature parameter λ (-1 to 1), the Darcy number (10^{-5} to 10^{-1}), the Rayleigh number (10^3 to 10^6), the Hartmann number (0 to 50), the solid volume fraction ϕ (0.01 to 0.03) of nanoparticles, and the Prandtl number (6.2).

Salma et al. [21] conducted a numerical study on unsteady natural convection flow and heat transfer within a square cavity filled with nanofluids, influenced by a periodic magnetic field. They varied the sizes and fractions of nanoparticles to enhance the physical realism of their investigation. The main dimensionless parameters examined in this study included a Rayleigh number (Ra) ranging from 10^4 to 10^6, a Hartmann number (Ha) between 25 and 100, a periodicity parameter (λ) from 0.1 to 1.0, nanoparticle volume fraction ($\emptyset$) between 0.01 and 0.05, and a dimensionless time (τ) varying from 0.01 to 1.

2.3. Previous studies with inner Bodies

2.3.1 Square inner Body

In a significant study, Sheremet et al. [22] conducted computational analyses to explore the effects of introducing solid isothermal bodies into a cavity filled with nanofluids that are cooled via an isothermal cooler positioned in one corner. The investigation focused on various geometric ratios of the solid mass and the isothermal coolant, in addition to factors like the nanoparticles' solid volume fraction and Rayleigh number respectively. Using nanoparticles improves heat transfer and decreases convective flow in the cavity, according to their research. Moreover, increased entropy creation within the cavity is linked to an increase in the Rayleigh number. The results, which are shown in Figures 7 and 8, show the average Bejan number, average Nusselt numbers, entropy generation profiles, simplifications, and isotherms that correspond to various values of the important parameters that were studied.

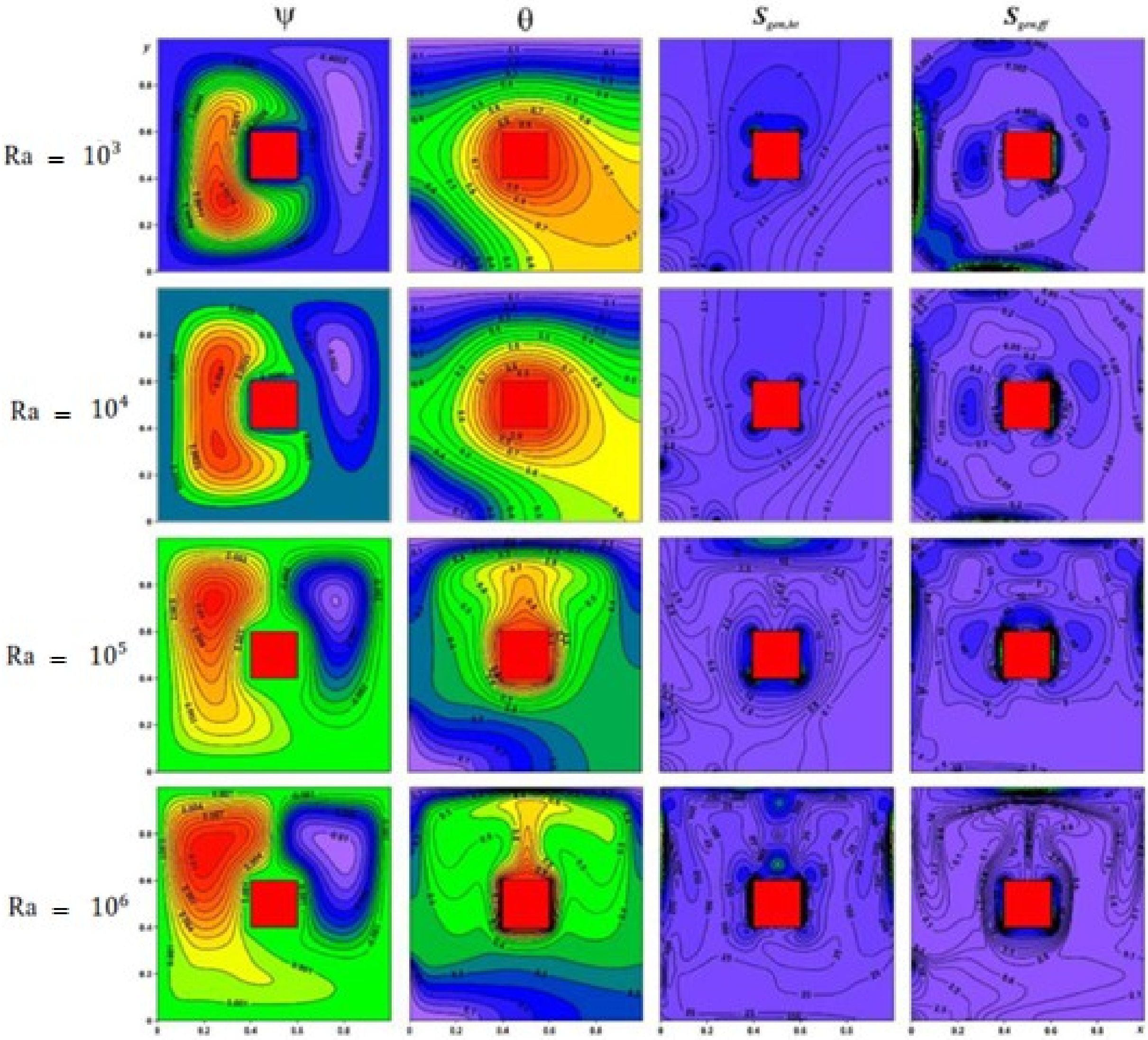


Figure 7. For l/L=0.2, h/L=0.25 and ϕ=0.03, streamlines ψ, isotherms θ, local entropy generation from heat transfer $S_{gen,ht}$, and local entropy generation from fluid friction $S_{gen,ff}$ [22]

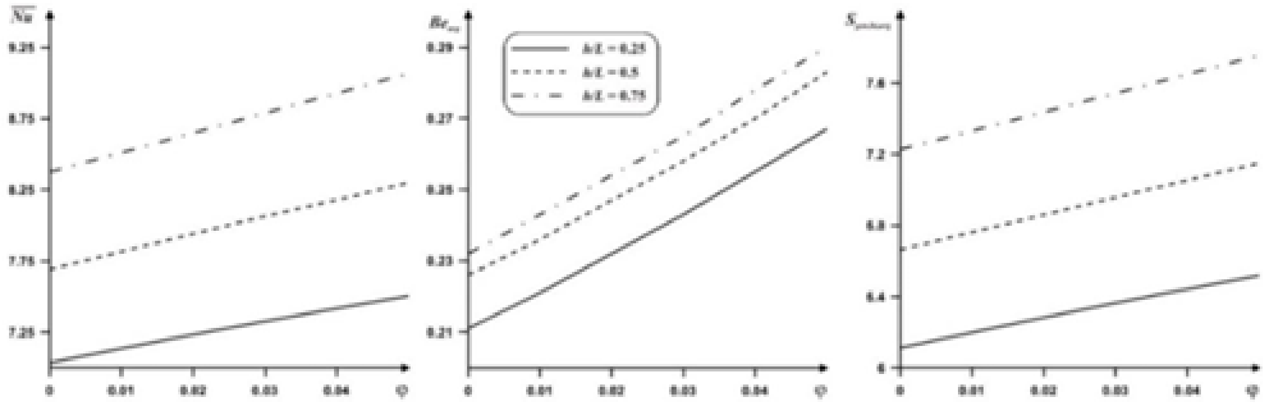


Figure 8. For Ra =10^5, l/L =0.2, the average Nusselt number (a), Bejan number (b), and entropy generation from heat transfer (c) are plotted against the volume % of nanoparticles and the dimensionless cooler length [22]

Bondareva and Sheremet [23] conducted a numerical study on natural convective melting in a square cavity with a localized square heat source, focusing on the effects of a tilted magnetic field. They employed a second-order finite difference method utilizing the enthalpy formulation to solve the governing equations, along with the corresponding initial and boundary conditions in both solid and liquid phases. Their results indicated that the magnetic field's inclination angle significantly influences the flow patterns, temperature distribution, and Nusselt number, particularly at a Hartmann number (Ha) of 0. Specifically, for inclination angles of α = 0 and α = π/2, they observed a symmetrical distribution of velocity and temperature within the melting zone. This study provides valuable insights into the interplay between natural convection, magnetohydrodynamics, and the Prandtl number in a square container containing an adiabatic square body.

Hussein et al. [24] conducted a numerical investigation of two-dimensional magnetic convection flow (MHD) within a square container filled with an electrically conductive fluid, employing the Lattice Boltzmann method (LBM). They explored a range of non-dimensional parameters, specifically varying the Hartmann number ($0 \leq Ha \leq 50$), the Rayleigh number ($10^3 \leq Ra \leq 10^5$), and the Prandtl number ($0.05 \leq Pr \leq 5$). Their findings revealed that as the Hartmann number increases, the magnetic field exerts a significant influence on the flow dynamics, particularly at higher Prandtl numbers. Notably, their results illustrated that the average Nusselt number decreases with an increase in the Hartmann number, as depicted in Figure 9. This study underscores the complex interplay between magnetic fields and convection phenomena in electrically conductive fluids.

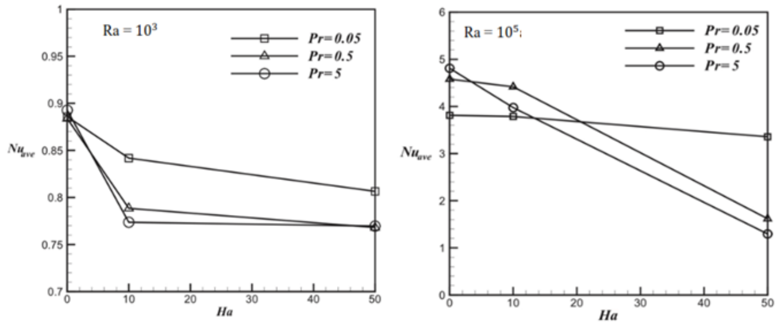


Figure 9. The Nusselt number average for different Hartmann and Prandtl numbers [24]

2.3.2 Elliptical inner body

El Moutaouakil et al. [25] performed a comprehensive two-dimensional numerical analysis to explore the interaction between natural convection and surface radiation within a horizontal toroidal region. This region is bounded by an inner heated elliptical cylinder and an outer square cavity. To investigate the natural convection phenomena quantitatively, the researchers merged the discrete arrangement approach with the finite volume method. Important factors were the ellipsoidal body's eccentricity ($00 \leq \xi \leq 0.98$) and inclination angle ($|\phi| \leq 90°$). Additionally, the impacts of the interior and exterior surfaces' emissivity and Rayleigh number were examined.

2.3.3 Inner circular body and cylinder

Wang et al. [26] adopted an improved lattice Boltzmann method to simulate conjugate natural convection in a square box with a circular cylinder. They performed simulations for Rayleigh numbers in the range of $10^4 \leq \mathrm{Ra} \leq 10^6$, with the radius of the cylinder ranging from 0.1H to 0.3 H, wall thickness from 0.05 H to 0.2 H, and thermal conductivity ratio from $0.5 \leq k_s/k_f \leq 20$. Unless otherwise stated, for all cases, the Prandtl number is fixed at 0.71, the wall-to-liquid heat capacity ratio is set to $(\rho c_p)_s/(\rho c_p)_f = 10.0$, and the inner cylinder has a radius R=0.2H, located at the center of the cavity. It was observed that the average Nusselt number (Nu_{av}) for a cavity with limited wall thickness is generally smaller than that for a cavity with zero wall thickness.

Mahmood et al. [27] investigated the natural convection of a horizontal cylinder placed in a square container numerically, using two different fluids as heat transfer mediums: water and air (Figure 10). They employed a 2D computational fluid dynamics (CFD) approach to predict natural convection when using water and air as the heat transfer media. Their results showed that the surface temperature significantly affects the Nusselt number when the cylinder is surrounded by air, with maximum velocities ranging from 0.007 m/s to 0.11 m/s.

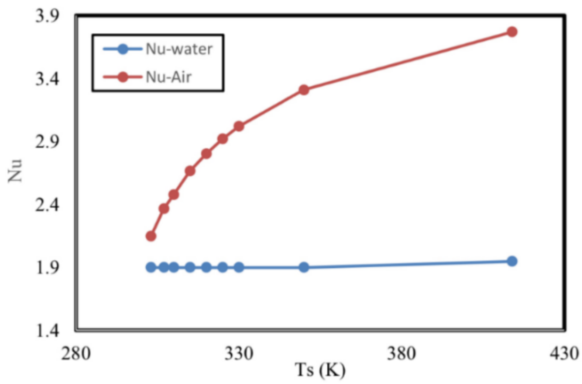


Figure 10. Nusselt number variation for air and water natural convection in relation to the horizontal cylinder's surface temperature [27]

Nammi et al. [28] numerically investigated unsteady natural convective heat transfer in a porous square container containing four heated cylinders arranged in either a square or rectangular configuration. The results are presented through simplifications, isotherms, and the time-average Nusselt number for the ranges $10^3 \leq$ Ra $\leq 10^6$, $10^{-4} \leq$Da $\leq 10^{-2}$, and four different cylinder spacings of 0.3 ≤ S≤ 0.6. Pandey et al. [29] conducted A numerical study in three dimensions of buoyancy-driven heat transfer for Rayleigh numbers (Ra) = 10^4-10^6 and Prandtl numbers (Pr) = 0.7 in a container with four heated cylinders. Their results indicated that the average time-averaged and surface Nusselt numbers on the cylinder surface increased with increasing ε_h, regardless of Ra (Figure 11).

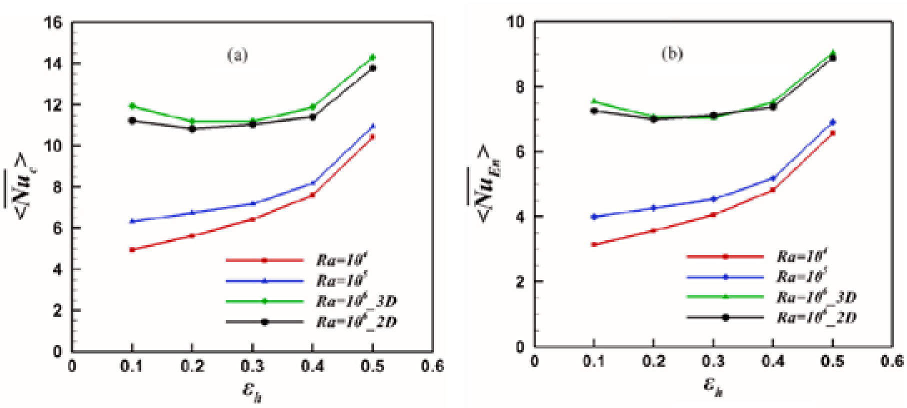


Figure 11. Nusselt number average across time and surface at (a) the cylinder and (b) the enclosure.[29]

2.3.4. Square enclosure with two wavy sided walls

Abdulkadhim et al. [30] numerically investigated natural convection heat transfer using the temperature gradient of a heated inner corrugated cylinder. Their study simulated various internal corrugation configurations within a refrigerated double-walled square container filled with two layers. They employed the Galerkin method to solve the main dimensionless equations numerically. The analysis considered several dimensionless parameters: Rayleigh number (10^3≤ Ra ≤10^6), Vertical location (-0.2 ≤ H≤ 0.2), the number of sinusoidal internal cylinders (3 ≤ N≤ 6), the Darcy number (0.00001 ≤ Da ≤0.1), the volume percentage of nanoparticles (0 ≤^{7}≤ 0.1), and the thickness of the porous layer (0.2 ≤ X_P≤ 0.8). Their findings suggested that when the fluid flow force increases, the inner sinusoidal cylinder should rise. A square container with a horizontal barrier at the center line of the left wall that contained water mixed with $AL_2O_3$and a magnetic field was used to study natural convection heat transfer.

Alsabery et al. [31] investigated natural convective heat transfer in a porous and undulating domain filled with non-Darcian nanofluids under conditions of local thermal non equilibrium A numerical solution of the non-dimensional transport equations was obtained by applying the Galerkin finite element differentiation method. Several parameters were taken into consideration in the investigation, including the modified conductivity ratio (10^{-1}≤ γ ≤10^{-4}), number of ripples (0 ≤ N ≤4), nanoparticle volume fraction (0 ≤ φ ≤0.04), and Darcy number (10^{-6}≤ Da ≤10^{-2}). The heat source's dimensionless position (0.2≤ B ≤0.8) and dimensionless length (0.2 ≤ D ≤ 0.8) were also investigated.

2.4. Triangular inside a square with MHD

Mahmuda and Ali [32] investigated the effects of a magnetic field on the partial heating and cooling of vertical walls in a square cavity filled with aqueous Al_2O_3 nanofluid by numerical study of free convective flow and heat transfer. A heat-conducting triangular cylinder was positioned centrally within the cavity. Using the weighted Galerkin residual method within a finite element formulation, they solved the dimensionless governing equations. The study explored the influence of key parameters, such as Rayleigh numbers (10^3≤ Ra ≤10^6), Hartmann numbers (0≤ Ha ≤100), and nanoparticle solid volume fractions (0% ≤ φ ≤ 5%), on velocity and temperature fields. Results demonstrated a notable increase in heat transfer rate with rising Rayleigh number, as the elevated Ra values intensified buoyancy forces, accelerating the rotational flow within the cavity (Figure 12).

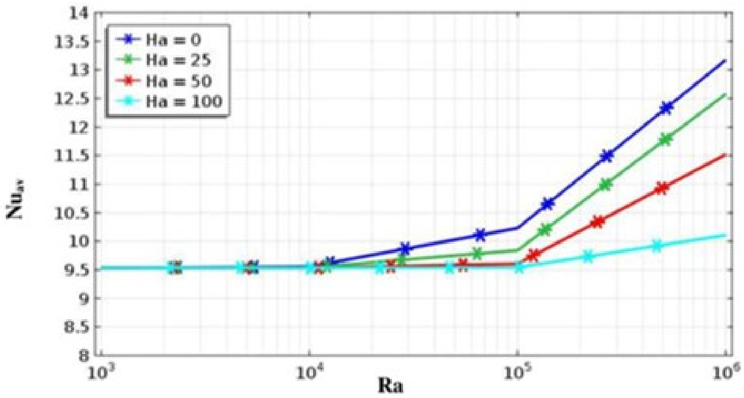
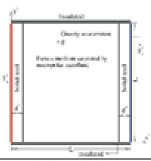
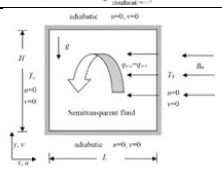
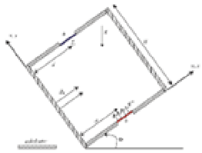
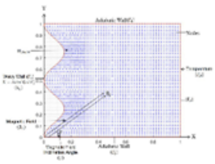
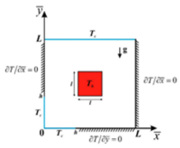
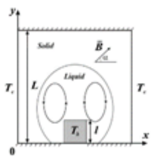
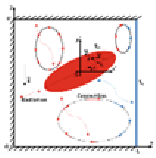
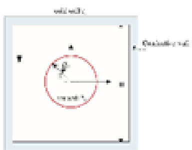
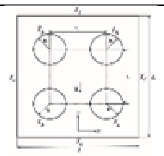
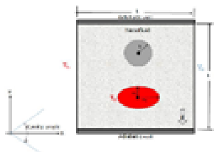
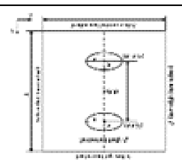
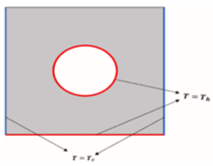


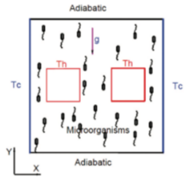
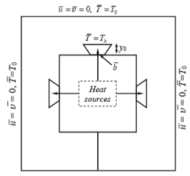
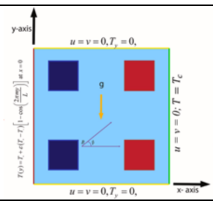
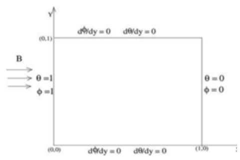
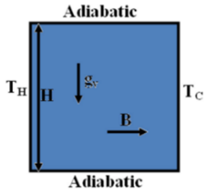
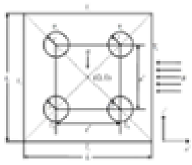
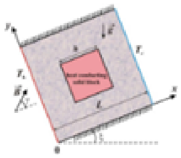
Figure 12 Effect of Hartmann number on Nusselt number average at partially heated side walls [32]

Altaee et al. [33] conducted a study on natural convection heat transfer in a square cavity containing an interior structure with an equilateral triangular cross-section. They used computational fluid dynamics (CFD) simulations with Ansys Fluent 16 to solve continuity, momentum, and energy equations. The study examined Rayleigh numbers ranging from 10^4 to 10^6 and orientation angles from 0° to 105°, with 15° increments for each case. Results revealed that the flow intensity was highly sensitive to oblique and rotational angles of the heated triangle, significantly altering both the streamline and temperature fields. When the triangle was at 0^0 and Rayleigh numbers were Ra = 10^5 and 10^6, the top of the triangle formed two nearly symmetric convection cells, consistent with typical natural convection patterns.

Table 1. A summary of the Effect of Different Internal and external bodies in Square Containers on Natural Convection

Reference	Major topic	Enclosure shape	Results
[8]	Micropolar nanofluid in porous media	Porous square enclosure 	Thicker solid walls increase the wall stress-to-fluid volume ratio at the fluid-solid interface.
[14]	MHD natural convection with radiation	Square enclosure 	The critical parameter Plc increases exponentially with Hartmann number (Ha) and decreases exponentially with Reynolds number (Re).

[16]	MHD natural convection of nanofluid	Inclined porous square cavity 	Maximum average Nusselt number occurs at B = 0.2 and inclination angles between 50° and 310°.
[21]	MHD heat transfer in nanofluids	Square cavity with magnetic fields 	Both average Nusselt number and heat transfer rate increase under uniform and periodic magnetic fields.
[22]	Natural convection of nanofluids	Square cavity 	Increasing the Rayleigh number enhances convective flow and heat transfer.
[23]	Local heat source and MHD-induced melting	Square cavity 	Nusselt number decreases over the top and vertical sides of the heater over time due to increasing heating demands in those regions.
[25]	Radiative natural convection	Elliptical internal body in square cavity 	At high Rayleigh numbers, streamlines rotate clockwise with vortex formation near the top-left corner.
[26]	Natural convection with cylindrical body	Circular cylinder in square cavity 	Heat transfer rate declines as the outer wall thickness increases.
[28]	Natural convection with internal heaters	Four heated cylinders in a square cavity 	Total Nusselt number (Nu_t) increases monotonically with cylinder spacing (S) for Darcy number $Da = 10^{-4}$.
[34]	Natural convection in inclined nanofluid	Heated, inclined square cavity 	Minimum stream function values are observed at high Rayleigh numbers when the caustic angle is -30°.
[35]	Dual heated inner cylinders	Two heated elliptical cylinders 	At $Ra = 10^4$–10^5, increasing aspect ratio (AR) enhances the time-averaged Nusselt number and surface heat transfer.
[36]	Convection with a circular obstacle	Fixed circular object in nanofluid-filled cavity 	Lamina nanoparticles enhance heat transfer and thermal distribution in diamond–water systems.

[37]	Dual internal heaters	Two heaters inside square enclosure 	Sherwood number increases by 31% when thermal Rayleigh number rises from 10^3 to 10^5 for Ra_b= 10.
[38]	Natural convection in composite geometry	Trapezoidal cavity with a central square cylinder 	Heat transfer across cavity walls and sources is significantly enhanced with higher Rayleigh numbers.
[39]	Sinusoidal boundary conditions and blocks	Square cavity with hot/cold blocks 	Stronger magnetic fields (higher Ha) suppress flow velocity and result in weaker, more symmetrical vortices.
[40]	MHD effects on convection	Square cavity 	Buoyancy ratio has minimal effect at low Rayleigh numbers and high magnetic field strength..
[41]	Laminar vs. turbulent MHD convection	Square cavity 	Heat transfer decreases with increasing Hartmann number at Ra = 10^5 (laminar) and Ra= 10^8 (turbulent).
[42]	MHD convection with multiple obstacles	Four circular cylinders in square cavity 	Increased magnetic field strength and ε significantly reduce oscillation frequency.
[43]	Conductive solid block in MHD convection	Square cavity with internal conducting block 	Average Nusselt number varies nonlinearly with the angle of the applied magnetic field.

2.5. Inner body studies without MHD

Rahmati and Tahery [44] Performed a two-dimensional simulation of natural convection heat transfer surrounding a heated obstacle within a square hollow, characterized by cold side walls, an adiabatic top wall, and a heated bottom wall. Using the capillary Boltzmann method, they analyzed transfer of heat in a water-TiO_2 nanofluid, Prandtl's number is 6.2 and a Rayleigh number of 10^6. The volume fraction of the nanofluid was 0.05. According to the study, when the volume fraction of nanoparticles rises while keeping the Rayleigh number constant, the average Nusselt number on the cold walls also rises. Additionally, with increasing Rayleigh number, the streamlines intensify near the cavity boundaries, becoming more pronounced as the Rayleigh number grows. Figure 13 illustrates the proximity of streamlines to the cavity edges under higher Rayleigh numbers.

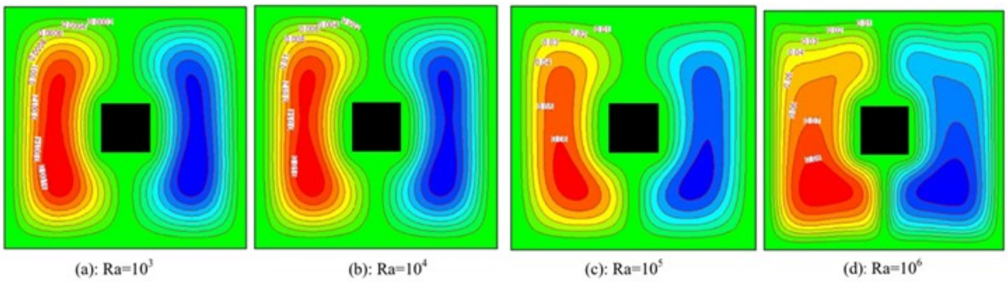


Figure 13. Streamlines for φ=0.04 and various Rayleigh numbers.[44]

Ali et al. [45] conducted a numerical analysis of natural convection in saturated porous media, applying the governing equations using the finite difference approach. They provided numerical results on heat transfer behavior for a modified Rayleigh number (Ra) ranging from 100 to 1000, examining two distinct section positions: Case 1 ($X_{P_1} = \frac{1}{4}, X_{P_2} = \frac{3}{4}$) and Case 2 ($X_{P_1} = \frac{3}{4},\ X_{P_2} = \frac{1}{4}$), with section lengths varying between 0.2 and 0.8. Their findings indicated that heat transfer through free convection improves with an increase in Ra values.

Rashid et al. [36] examined the influence of nanoparticle morphology on nanofluid dynamics in a lid-driven square cavity with a stationary circular obstruction at the center. The research employed the finite element technique (FEM) to resolve the linked partial differential equations that dictate the flow. They considered the Prandtl number to be constant at Pr = 6.8. As shown in Figure 14, their results revealed that the velocity and temperature of the water-diamond nanofluid were inversely and directly related, respectively, to the angular momentum (φ).

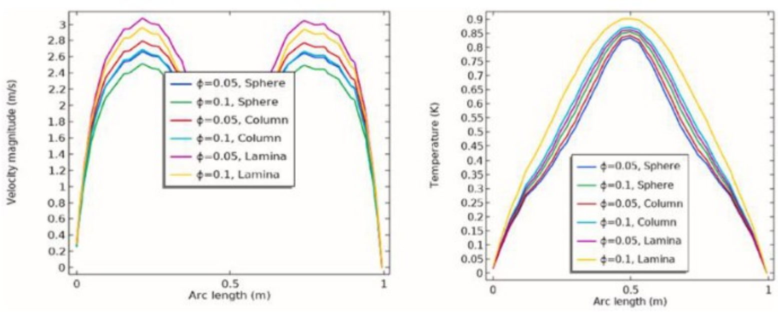


Figure 14. Variation in velocity and temperature of nanofluid with the impact of ϕ [36]

Izadpanah et al. [37] examined the natural biothermal convection of gyrotactic microorganisms in a square cavity containing two smaller square heat sources. They applied the finite element method (FEM) to assess microorganism dynamics and buoyancy-driven convection. Their research examined the impact of many parameters, including the thermal Rayleigh number (Ra_t, spanning from 10^3 to 10^5) and the biothermal Rayleigh number (Ra_b, ranging from 10 to 100). heater movement, the Peclet number (0.001–0.1), and the Lewis number (Le, between 1 and 10), on mass transport (Sherwood number) and natural convective heat transfer (Nusselt number). performance. Fixed parameters in the study included the oxygen diffusion rate (σ =1) and the ratio of oxygen diffusion to microorganism diffusion (χ = 1).

Roy et al. [38] investigated the characteristics of heat transmission and natural convection in an annulus made up of two square cylinders. By applying coordinate transformations, they developed a mathematical model for their system, which included three heat sources positioned at ξ = 90°, 180°, and 270° with parameters of width w= 0.10, breadth b = 24°, and Rayleigh number Ra = 10,000. Results demonstrated that increasing the number, width, and amplitude of heat sources, as well as the Rayleigh number, amplified flow strength. Figure 15 illustrates the effect of heat source width on the Nusselt number, particularly at the heat source top and on the cavity's outer walls.

Hamid et al. [46] examined the natural convection phenomenon in a square cavity with a unique curvature containing circular obstructions. They employed Galerkin weighted residuals as a numerical simulation technique, exploring the impact of three axial parameters: the Hartmann number, which ranged from 0 to 200, and the circular obstacle's radius, which systematically changed from 0.1 to 0.3 to capture various obstacle sizes. The Rayleigh number was varied between 10^2 and 10^7, while maintaining a constant Prandtl number of 6.2.

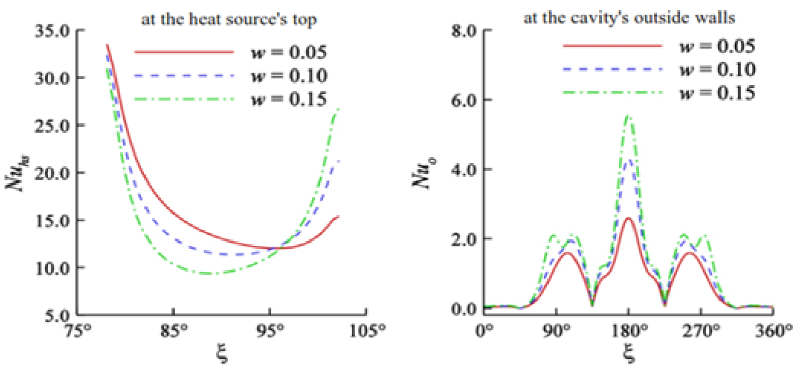


Figure 15. Effect of Nusselt number [38]

Another study [39] focused on the properties of Convection in two dimensions using magnetohydrodynamics (MHD) in a rectangular chamber containing an electrically conducting fluid. This investigation included a broad spectrum of governing parameters, such as inclination angle ($0 \leq \beta \leq 90°$), porosity ($0.1 \leq \varepsilon \leq 0.9$) Rayleigh number ($10^4 \leq Ra \leq 10^7$), Hartmann number ($0 \leq Ha \leq 500$), and a parameter m ($1 \leq m \leq 6$). The findings showed that the simplification inside the cavity increased by 445% and 5284% when the inclination angle (β) was enhanced from 0° to 90° and Rayleigh number (Ra) from 10^5 to 10^7, respectively. Conversely, simplification decreased by 1627% as Hartmann number (Ha) varied from 0 to 100. Additionally, heat transfer improved by 58% as porosity (ε) changed from 0.1 to 0.5. Overall, the findings revealed that larger inclination angles significantly enhanced heat transfer efficiency by reducing convective heat losses and improving fluid movement regulation.

2.6. Conventional Enclosure without inner body

Arjun and Rakesh [47] studied the simulation of fluid flow and natural convection heat transfer in a differentially heated square cavity that featured horizontal adiabatic walls and vertical isothermal walls, equipped with several fins. They employed the finite volume method to analyze the flow of Cu-water nanofluids containing non-uniform nanoparticles (R = 0.007) at an average diameter of 50 nm, maintained at a temperature of 333.15 K. The aspect ratio was set to 3, with three thin horizontal conductive fins connected to the hot wall, and the fins positioned at 0.4 of the height of the cavity. Their simulations, conducted under a Hartmann number of 10 and a Rayleigh number of 10^6, showed that the configuration achieved optimal heat transfer enhancement, maximizing the cold wall's average Nusselt number. They concluded that using three fins provided the best enhancement for heat transfer performance.

Reddy and Murugesan [40] conducted a numerical study on natural dual-diffusion convection in a square cavity subjected to an external magnetic field, employing the weighted Galerkin residual finite element method with a vortex velocity formulation. Their simulations covered a range of parameters: Hartmann number ($0 < Ha < 200$), Rayleigh number ($10^4 < Ra < 10^6$), and field inclination angles from 0° to 360°. The study explored various fluid systems, including gas, water, and liquid gallium.

Their results indicated that increasing the Hartmann number from 0 to 30 resulted in a significant decrease in the Nusselt number and Sherwood number by approximately 72% and 78%, respectively. Figures 16 and 17 illustrate the simplified profiles, isothermal lines, and concentration lines for Rayleigh numbers of 10^4, 10^5, and 10^6 when the magnetic field is applied horizontally at N = 0.75, Pr = 1, and Le = 2.

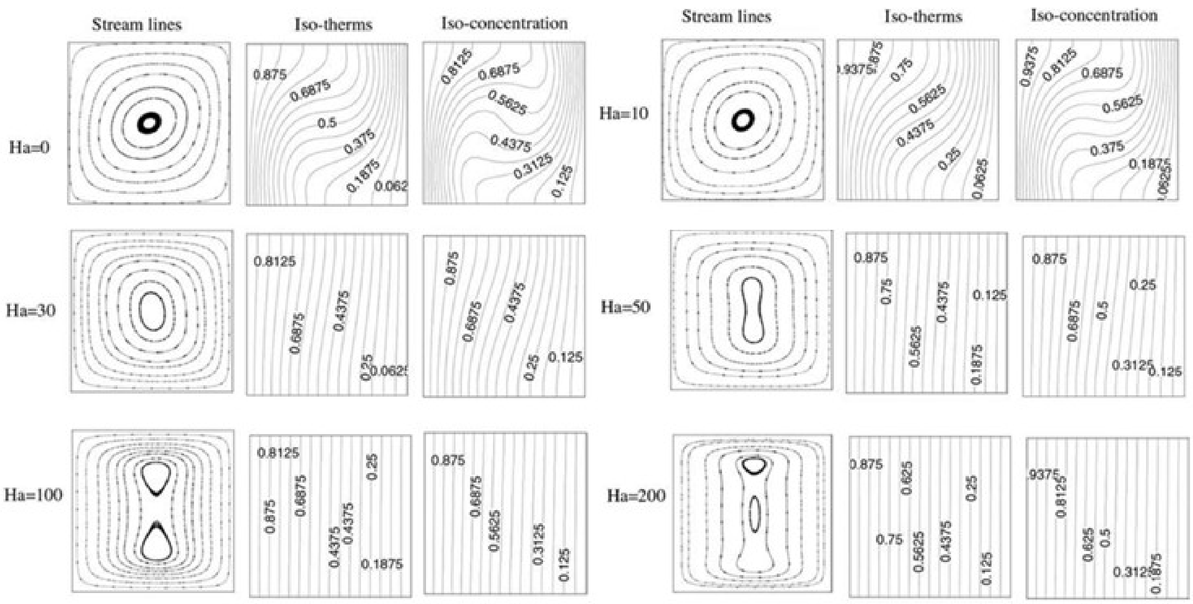


Figure 16. Hartmann number's impact on streamlining, isotherms, and isoconcentration lines at Ra = 10^4 for N = 0.7.[40]

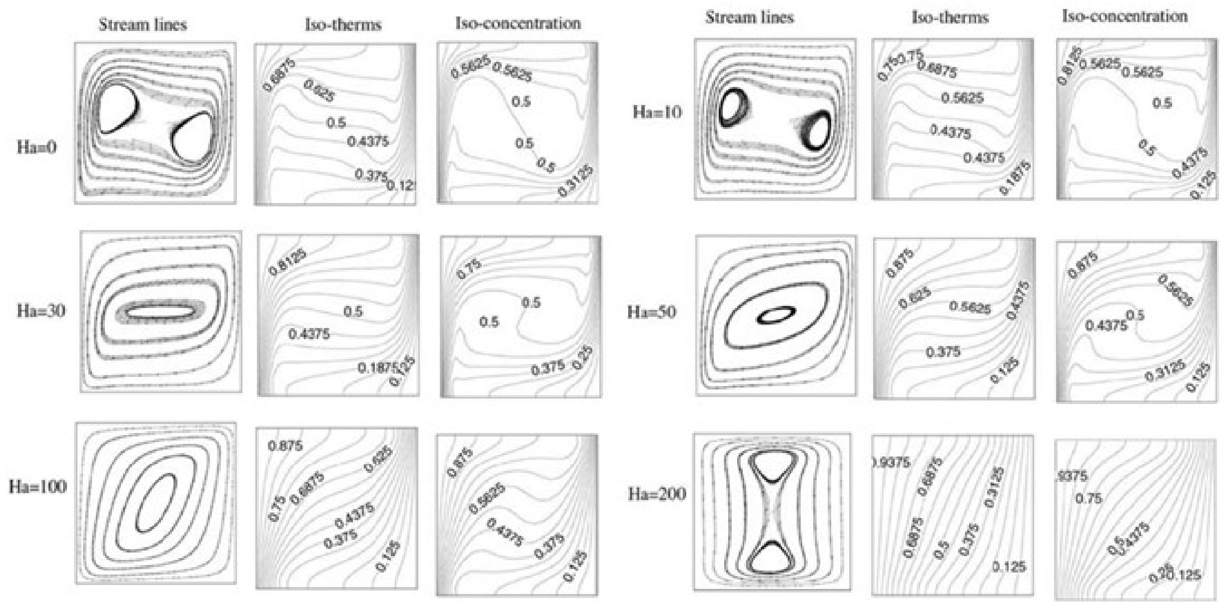


Figure 17. Hartmann number's impact on streamlining, isotherms, and isoconcentration lines at Ra =10^6 for N = 0.75. [40]

Sajjadi and Kefayati [41] applied the lattice Boltzmann method to analyze both turbulent and laminar natural convection within a square cavity containing water (Pr = 6.2). Their study considered Rayleigh numbers in the ranges Ra = $10^3 - 10^5$ for laminar flow and Ra = $10^7 - 10^9$ for turbulent flow, along with Hartmann numbers (H = $0 - 100$). They observed that the magnetic field had a significant influence on heat transfer, especially at Ra = 10^5, where increasing Ha from 0 to 100 led to a notable reduction in heat transfer. Figure 18 illustrates the local Nusselt number distributions on the hot and cold walls under various Rayleigh and Hartmann numbers.

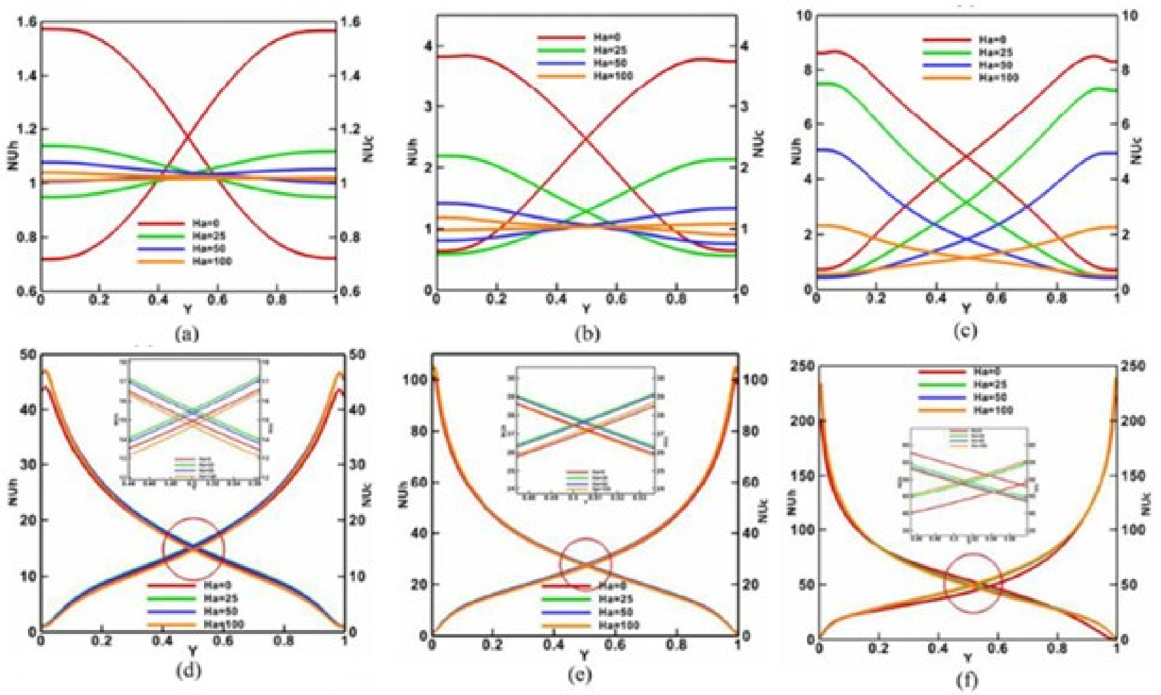


Figure 18. Effect of Rayleigh and Hartmann values on the Nusselt number on the hot and cold walls (Ra = 10^3, 10^4, 10^5, 10^7, 10^8 and 10^9) [41]

2.6.1. Inner body studies with MHD

Chatterjee and Kumar [42] conducted a finite-volume numerical study to explore two-dimensional hydromagnetic natural convection in a cooled square container containing four uniformly shaped, heated inner circular cylinders. They assumed all solid walls were electrically insulated. The simulations covered various control parameters, including Rayleigh numbers from 10^3 to 10^6, Hartmann numbers from 0 to 50, and dimensionless distances between cylinder centers ranging from 0.3 to 0.7. The study's primary goal was to analyze how the placement of the cylinders along the case's diagonals influences magnetic heat transfer within the cavity.

Tayebi and Chamkha [48] studied natural convection of an AL_2O_3-Cu/water hybrid nanofluid in a cavity containing a centrally positioned corrugated conductive cylinder under a constant horizontal magnetic field. They utilized the finite volume method (FVM) to solve the governing transport equations. Parameters were analyzed based on various factors, specifically the average Nusselt number (Nu_{avg}) for different thermal conductivity ratios (k*) at a nanoparticle volume fraction (ϕ) of 0.06, corrugation amplitude (A) of 0.2, and Hartmann number (Ha) of 25, with Rayleigh numbers of Ra = 10^3 and Ra = 10^5. Their findings revealed that alumina nanoparticles in water enhanced heat transfer significantly, especially under convection-dominated conditions.

2.6.2. Previous studies without inner body and Without MHD

Khalili et al. [49] investigated natural convection heat transfer of a nanofluid in a two-dimensional square cavity using the lattice Boltzmann method with constant heat flow boundary conditions. They explored parameters such as Rayleigh numbers (Ra = 3.5×10^5, 3×10^6), constant streamline, velocity, average Nusselt number, and temperature throughout volume fractions of nanoparticles (φ = 0.05, 0.1, 0.2). According to their findings, the Nusselt number rose as the volume fraction of nanoparticles increased, indicating improved heat transmission in the nanofluid as opposed to the pure fluid, even with a fixed Grashof number. The dimensionless temperature distribution, velocity profiles, and simplifications for water at Ra* = 3.5×10^5 and Ra* = 3×10^6 are shown in Figure 19 of their paper.

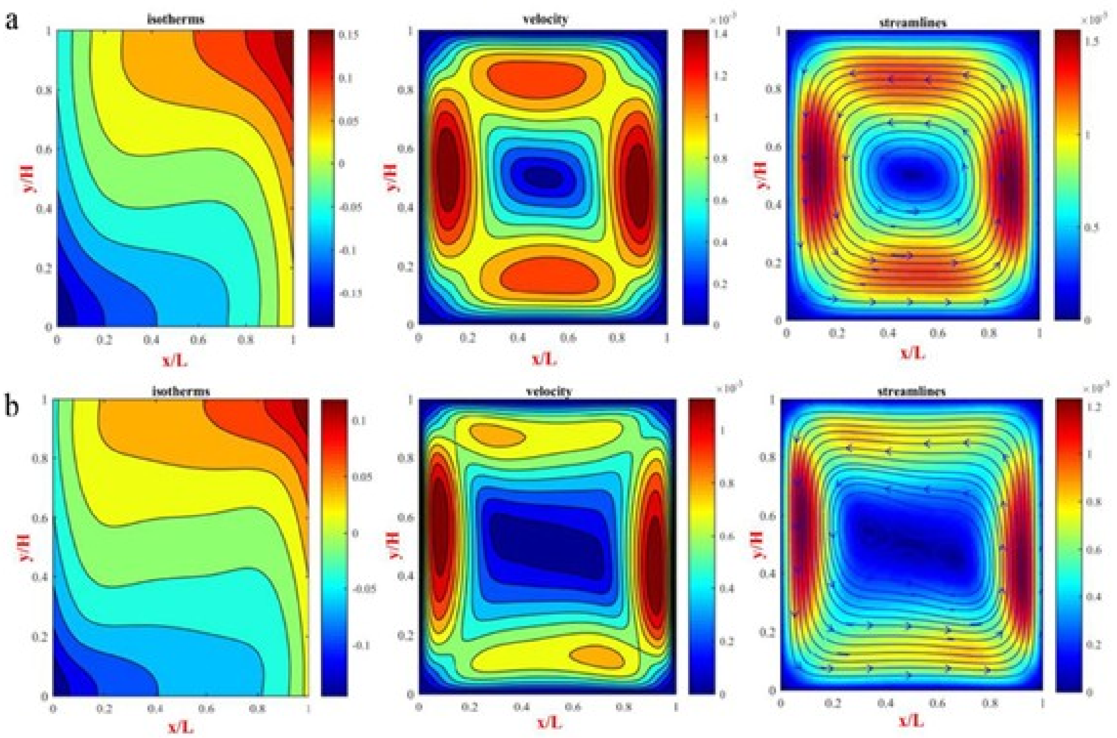


Figure 19. Water temperature distribution, velocity, and streamlines Ra* values for a and b are 3.5×10^5 and 3×10^6, respectively.[49]

3. Conclusion

The reviewed studies clearly show that the size and position of internal bodies within square enclosures play a pivotal role in influencing natural convective heat transfer. Variations in these parameters significantly alter the flow circulation and heat distribution patterns, affecting the overall heat transfer performance. Future research should focus on systematically analysing how incremental changes in size and position can be optimised to improve thermal efficiency. The influence of internal body size and positioning is evident across various studies, demonstrating its critical role in enhancing or suppressing heat transfer depending on the configuration. Optimizing these parameters, in combination with factors like nanofluid application and magnetic field strength, can significantly improve thermal performance. These insights can be useful in designing more effective thermal management systems in engineering applications.

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