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A Comprehensive Review of Nusselt Number Enhancement of Natural Convection in Literal Shapes Cavities: Recent Trends and Future Challenges

Hussien Aziz Saheb[1*], Ahmed Kadhim Hussein[2]

[1] Ministry of Construction, Housing, Municipalities and Public Works, Diwaniya 00964, Iraq
[2] Mechanical Engineering Department, University of Babylon, College of Engineering, Hilla 00964, Iraq

Corresponding Author Email: eng419.hussien.aziz@student.uobabylon.edu.iq

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ABSTRACT

This research review analyzes a group of previous studies that focused on improving natural convection in literal-shaped cavities filled with base fluids (H_2O or other), nanofluids, or hybrid nanofluids. This work attempts to provide an in-depth and integrated understanding of how the complex geometry of cavities affects the boosting of heat transfer and heat exchange efficiency. Highlighting the thermophysical properties of these different fluids. The current study sought to review the most prominent engineering applications and research challenges associated with this field. This study attempts to explore recent trends in improving thermal performance through the use of unconventional fluids, and to analyze various factors such as Raleigh number (Ra), Prandtl number (Pr), Volume Fraction (φ), viscosity, and thermal conductivity. Numerous studies have addressed natural convection in classical cavities, whereas complex cavities (such as U, V, C, L, E, H etc.) still need further study, which constitutes a scientific gap that can be explored.

1. INTRODUCTION

One of the major disadvantages of conventional fluids is known to be low thermal conductivity and critical heat flow. Conventional fluids are water, oil, and others [1-3]. Masuda et al. [4] were the first pioneers in scientific research related to enhancing the thermal conductivity of base fluids. All studies indicate that Maxwell [5] was the first to present the idea of suspending solid nanoparticles in nanofluids to raise their thermal properties. Still, the lack of advanced technology at the time made it impossible to work with nanoparticles. researchers began conducting many different studies and researches to explore different aspects of nanofluids, Sadeghi et al. viscosity [6-8], thermal conductivity [9-11], heat transfer performance [12-14], Artificial intelligence applications for predicting various properties of nanofluids [15-17], and Engineering applications [18-20]. Many review papers summarize the most important research results of nanofluid studies in various aspects [21-23]. The particles size added to base fluids directly affects the properties of fluid, as micro particles lead to increased viscosity and increasing the drop of pressure due to their rapid settlement in the base fluid [24-26]. Choi and Eastman [27] were the first to advocate suspending solid nanoparticles in base fluids to enhance heat transfer and thermal properties. Nanoparticles (d≤100 nm) were suspended in water strengthen heat transfer through improving thermal conductivity in base fluids. Three mechanisms of heat transfer in fluids: free, forced, and mixed convection [28, 29]. Dahani et al. [28] found that the use of a (water/Ag) in a square cavity improved heat transfer. Chen et al. [30] concluded that suspending the nanoparticles in the base fluid, a slight change in the streamline of free convection and contours of temperature, these changes are more noticeable for forced convection. Sheikholeslami et al. [31] examined the thermophoresis and Brownian motion through a cavity filled with (alumina/water). While one of them studied effect of porous cavity medium on $N\bar{u}$ number [32].

Nowadays, complex geometries cavities have become interesting and a focus of attention in various industries such as renewable energy, HVAC, Cooling equipment, solar collectors and electronic devices. The cavity geometry was considered one of the important parameters related to enhancing heat transfer through the cavities, as different shapes were used rectangular, triangular, and trapezoidal cavity [33-35], Sun and Pop [36] used three types of nanoparticles to investigate characteristics of temperature and $N\bar{u}$ in a porous triangular cavity.

Many researches and studies were conducted and dealt with many parameters and boundary conditions to demonstrate how to elevate heat transfer, such as focus on the effect of a wavy wall [37], heat generation [36], heat flux [37], and wall temperature [38].

Al-Zamily [40] conducted a numerical study to investigate the influence of a uniform magnetic field on natural convection within a semi-circular cavity filled with Cu–water nanofluid under partial heat flux conditions. The findings revealed that the heat transfer rate increases with higher (Ra) and greater nanoparticle volume fractions, whereas it decreases as the (Ha) increases.

Hatami et al. [39] examined natural convection in a wavy cavity. Cosine function was presumed for the inner wall equation, the heat transfer and Nu increased rapidly. Many

modern technologies, such as nuclear reactors, highlight the importance of nanofluids with magnetic fields in various cavities [41]. Nemati et al. [42] evaluated the effect of magnetic field on natural convection through a rectangular cavity. They concluded that increasing the magnetic field intensity reduces the rate of heat transfer in the cavity. Various numerical methods, including (FDM), (FVM) and (FEM) methods were used to solve various problems of natural convection [8]. The important prediction tool used to solve natural convection problems is the Lattice Boltzmann method (LBM) [43, 44]. Sheikholeslami et al. [45] used LBM and a cylindrical cavity to study the natural convection. Natural convection in a wavy circular cavity was examined by Hatami [46]. Triangular cavities as well as 3D Regular Shape Enclosures were excluded because they were previously addressed in the research of Ghoben and Hussein [47, 48]. Walker and Homsy [49] investigated the effect of the (Da) on the (Nu) by analyzing the natural convection in a porous cavity. The basic idea of this research review is to provide a comprehensive review of studies conducted on natural convection in letter-shaped cavities (H-E-I-C-L, and U). This review provides very important information about the methods and techniques used recently. It also presents a comprehensive overview of both strengths and weaknesses, and most importantly, the amazing results of studies conducted in this field. Although many experimental and numerical studies have been conducted to review the mixed and forced convection of nanofluids in cavities, no one has studied the overview of natural convection of nanofluids in letter-shaped cavities. In the following sections, the literature on natural convection of nanofluids in literal shapes cavities will be presented and discussed. Moreover, the general trend of research papers published in recent years will be presented, addressing the most commonly used nanoparticles, in order to provide a clear view and give a comprehensive idea of the studies carried out in this specialized field. According to the works examined in this review, there are a limited number of studies in the scientific literature that have been conducted to investigate the natural convection of nanofluids in letter-shaped cavities. On the other hand, there is only little research, most of which focused on mixed or forced convection, while natural convection has not been adequately addressed. This review has highlighted a scarcity of experimental studies on natural convection in geometrically literal cavities, emphasizing the need for practical implementation to better understand its behavior and demonstrate its significance across various engineering applications. It is worth noting that the majority of the studies reviewed herein are limited to laminar flow conditions. Consequently, there exists a significant research gap in exploring transitional and turbulent regimes, which are crucial for accurately modeling real-world thermal systems and enhancing the reliability of numerical predictions. In the next section (2), the literal-shaped cavities are discussed and divided into five categories based on the shapes of the cavities.

2. CAVITIES WITH LITERAL SHAPES, THEIR TYPES AND THEIR IMPORTANCE

Letter-shaped cavities are geometric structures shaped like letters of the alphabet (such as H, L, T, U, C, E) and are used to improve natural convection in thermal applications. The design of these cavities differs from classical cavities (rectangular, square, circular), as the literal design allows better control of fluid flow and improved heat distribution within the cavity. literal-shaped cavities can be classified based on their geometric shape and the way the fluid flows inside them.

2.1 H-shape cavities

Keramat et al. [50] used single-phase model to solve natural convection in a H-cavity with V-shaped baffle. They studied the effect of (AR, φ, and Ra) on Nu, as shown in the Figure 1, The baffle position affects $N\bar{u}$, the top baffle reduces heat transfer, while the bottom baffle increases heat transfer. Additionally, a non-adiabatic baffle improves heat transfer more than an insulated baffle in the H cavity.

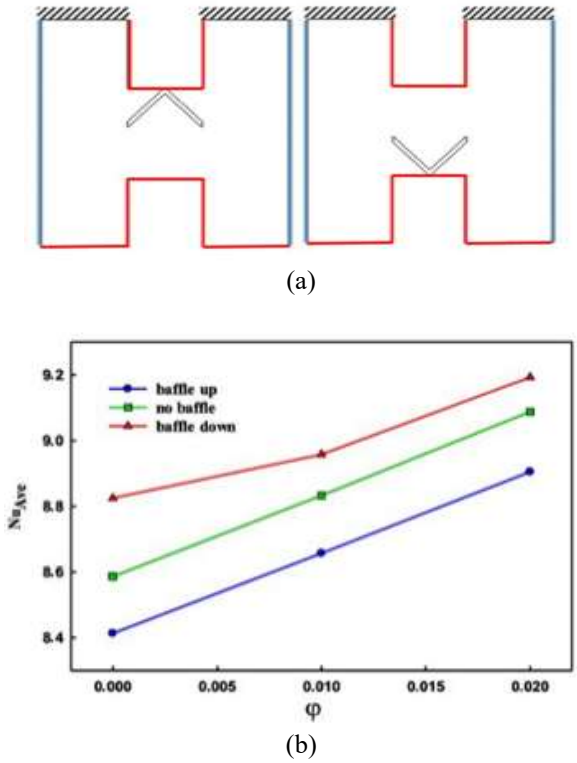

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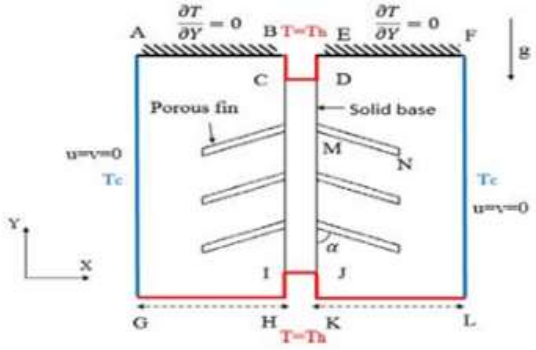
Figure 1. (a) Cavity geometry, (b) Baffle effect on $N\bar{u}$ [50]

Keramat et al. [51] studied the free convection in an H-cavity with six porous inclined fins as shown in Figure 2(a). This study was conducted numerically by examining several key parameters Ra (10^3–10^5), porosity (ε=0–1), AR (0.1, 0.2) Da (10^{-10}–10^{-2}), and angle of fin (68°, 90°, 112°). They found that the max heat transfer was at α=90° and AR=0.2, with a 60% increase in Nu for the porous fins. At low Da level (<10^{-6}), the porous fins are found to be like solid fins, while high Ra and porosity improved heat transfer as shown in Figure 2(b).

Loukili et al. [52] used (GFEM) to analyze natural convection in an H-cavity as shown in Figure 3(a). The cavity is filled with air. Important parameters include the (Ra=10-10^6) and ratio of internal height (0%, 50%, 85%). This research found that increasing Ra enhanced heat transfer and generated multiple vortices, while higher internal height ratio reduces flow of fluid and weakens heat transfer. (Nu) increased and reaching its peak at Ra=10^6 due to enhanced natural convection. In contrast, increasing the internal height ratio reduces Nu by restricting flow of fluid. The max heat transfer condition occurs at Ra=10^6 with 0% internal height ratio, as illustrated in Figure 3(b).



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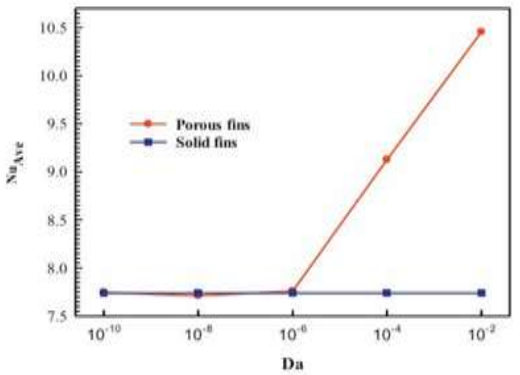

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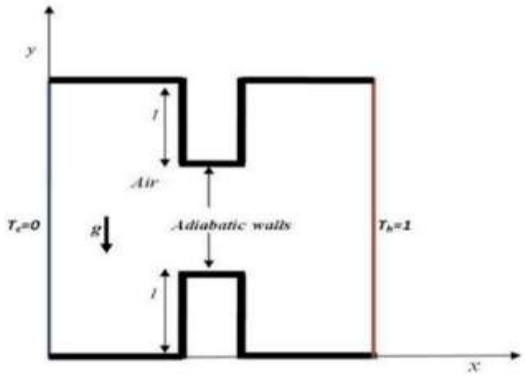
Figure 2. (a) Cavity geometry, (b) Porous fin effect on Nū [51]



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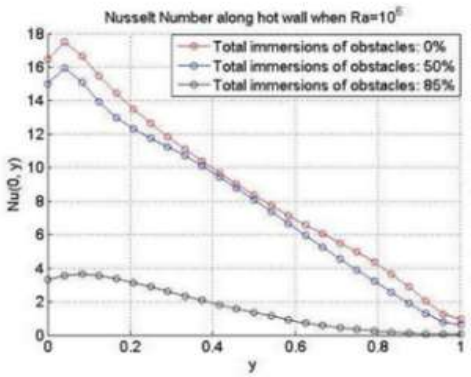
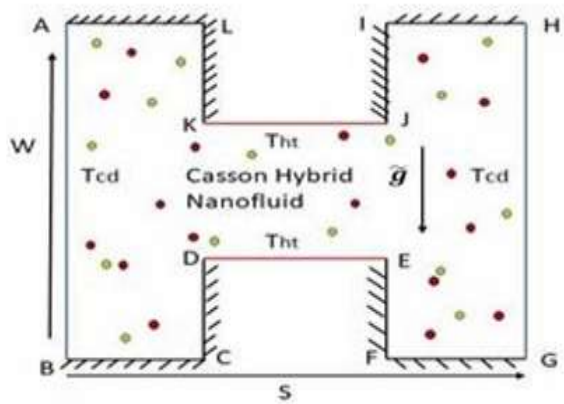


(b)

Figure 3. (a) Cavity geometry [52], (b) The effect of height aspects on the local (Nu)

Nadeem et al. [53] used the (GFEM) to simulate natural convection. Figure 4(a) shows H-cavity filled with (Cu–Al_2O_3–H_2O). The main parameters analyzed include ($Ra=10^3$–10^6), (AR=0.1–0.4), Casson parameter (γ=0.1–2), and (φ=0.005–0.020). Results indicate that increasing Ra, γ, and φ enhances heat transfer, while a higher (AR) reduces (Nū). The optimal heat transfer is achieved at η=0.1, $Ra=10^6$, and φ=0.020, where the convective effects are maximized. Max heat transfer at AR=0.1 and AR=2, where (Nū) reaches its highest value. Increasing AR reduces heat transfer, while increasing γ improves thermal flow by lowering viscosity and enhancing natural convection as shown in Figure 4(b).



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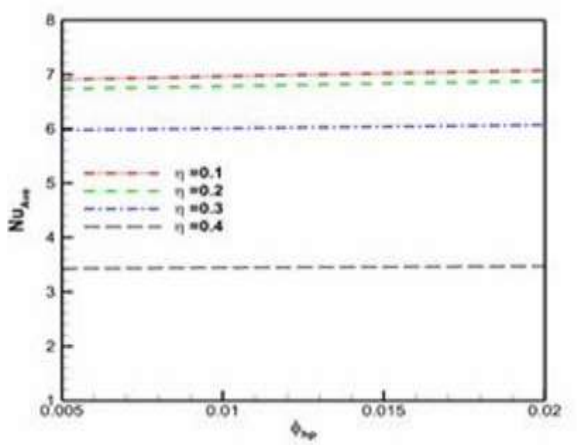

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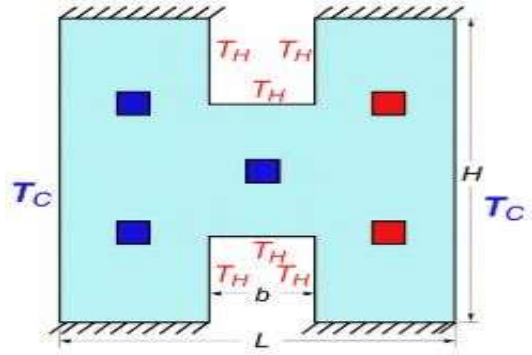
Figure 4. (a) Cavity geometry [53], (b) The effect of (φ and AR) on Nū [53]

Rahimi et al. [54] studied the natural convection in an H-cavity filled with $SiO_2/TiO_2/H_2O$-EG as shown in Figure 5(a), this study used a numerical method (LBM) with entropy generation analysis. The basic parameters in this numerical research included: ($Ra=10^3$–10^6), (φ=0.5%–3%), aspect ratio variations, and internal body arrangements. The results of this study as show in Figure 5(b) at higher Ra enhances heat transfer due to stronger convection, while a higher (φ) enhanced thermal conductivity, leading to a higher Nu. However, an increase in the (AR) tends to suppress the overall convective performance, resulting in a lower (Nu) due to constrained flow circulation. Conversely, optimal heat transfer enhancement is achieved under conditions of high (Ra) and elevated (φ), where buoyancy-driven convection is dominant and thermal transport is significantly intensified.



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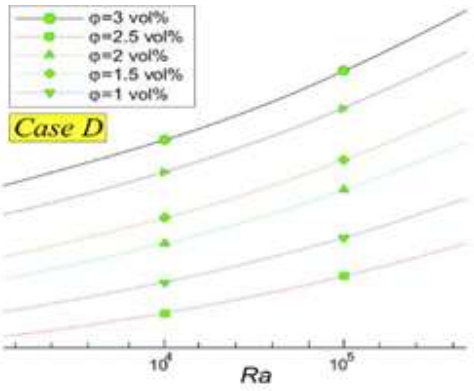

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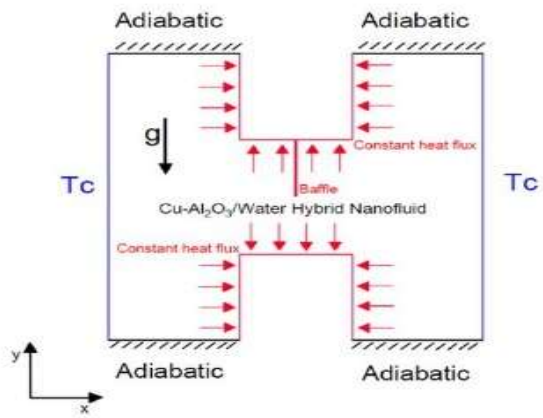
Figure 5. (a) Cavity geometry, (b) The effect of (Ra, φ) on Nū [54]



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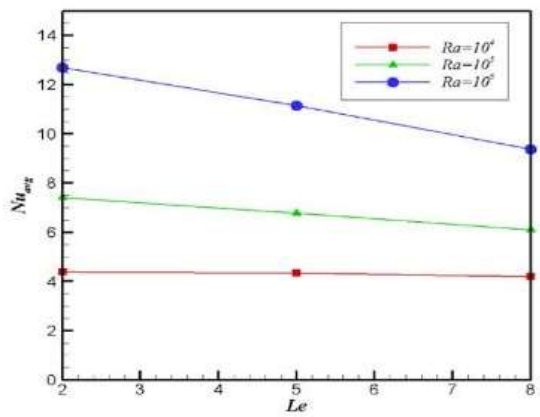


(b)

Figure 6. (a) Cavity geometry, (b) The effect of Ra and Le on Nū (N=3) [55]

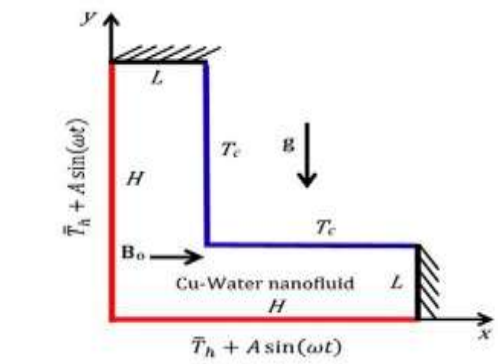
Eshaghi et al. [55] studied double diffusive natural convection in an H-cavity with a corrugated wall and baffle (Figure 6(a)). A hybrid nanofluid was simulated ($Cu/Al_2O_3/H_20$). Main parameters examined included ($Ra=10^4 – 10^6$), baffle inclination angle (-60° to +60°), Lewis number (Le=2–8), Buoyancy ratio (N=1–3), and (AR=0.375–1.5). This study reached with an increase in the Ra and N, heat transfer is enhanced, while in the case of an increase in Le, the Nū and Sh_{avg} decrease. The optimal configuration for maximum heat transfer is at θ=-60° without corrugation, while θ=+60° without corrugation gives the optimal performance of mass transfer. Figure 6(b) presents the impact of (Ra), (Le), and buoyancy ratio (N) on both heat and mass transfer within the H-shaped cavity. The (Nū) and (Shavg) increase with higher values of Ra and N, indicating enhanced convection due to stronger buoyancy forces. In contrast, increasing the Lewis number (Le) leads to a decrease in both Nū and Shavg, as higher Le suppresses thermal and mass diffusion. The most efficient heat transfer performance is achieved at $Ra=10^6$ and N=3, while elevated Le values are associated with reduced overall transfer efficiency.

2.2 L-shape cavity

Saleem et al. [56] examined natural convection under a time-periodic temperature boundary and field of magnetic in an L-cavity filled with Cu/H_2O as show in Figure 7(a). they used ($10^3 \leq Ra \leq 10^8$), ($0 \leq Ha \leq 100$), ($0 \leq \varphi \leq 0.2$), ($0.2 \leq AR \leq 0.8$), ($0 \leq f \leq 100$), and ($0 \leq A \leq 2$). This study found that as the Ra decreases, conduction dominates, while as the Ra increases, the effect of convection increases. Increasing Ha suppresses convection, reducing heat transfer, however nanofluid improved it, particularly at low Ha. The ideal heat transfer occurs at AR=0.2, with best temperature oscillation at f≈6. Figure 7(b) showed that the thermal oscillation will improve the natural convection, the value of Nu* increases with frequency (f), and reaches its highest value at f≈6 before it decreases. This happens due to improved fluid circulation, which leads to enhanced heat transfer. At low frequencies the effect is minimal, while at the optimal frequency the oscillations will correspond to the movement of the fluid, and thus efficiency will increase, while at higher frequencies viscous forces lead to reduced efficiency.

Suchana et al. [57] investigated natural convection in an L-cavity, and used $MWCNTs/H_2O$ as shown in Figure 8(a). This study adopted a numerical model the Multiple-Relaxation-Time (LBM). key parameters, including ($3\times10^3 \leq Ra \leq 3\times10^5$), ($0.0 \leq \varphi \leq 0.01$), Buoyancy ratio ($-2 \leq Br \leq 2$), Soret number ($0.0 \leq Sr \leq 0.2$), and Dufour number ($0.0 \leq Df \leq 0.2$). The results of this research demonstrated that increasing Ra, φ, and Sr improves mass and heat transfer (Nu and Sh increase) as shown in Figure 8(b), max Nu at $Ra=3\times10^5$. A higher φ enhanced thermal conductivity, leading to an increase in local Nu, but reduces local (Sh). Furthermore, entropy generation rises with Ra, while the Bejan number remains constant.

Nia et al. [58] analyzed natural convection of $Cu\text{-}H_2O$ in a baffled L-cavity. They examined the effects of ($10^3 \leq Ra \leq 10^5$), ($0 \leq \varphi \leq 0.05$), and baffle configurations length ($15 \leq L \leq 30$) cm, position S=40 cm, 60 cm. Results of this study showed that at low Ra (10^3-10^4), a baffle always improves heat transfer, Whereas at high Ra (10^5), only a long baffle (L=30 cm) enhanced convection. Figure 9(a) showed the geometry of cavity while (9-b) shows the best performance is achieved with case C (L=30 cm, S=40 cm), which maximizes (Nu), making it the optimal design for efficient management of heat transfer.



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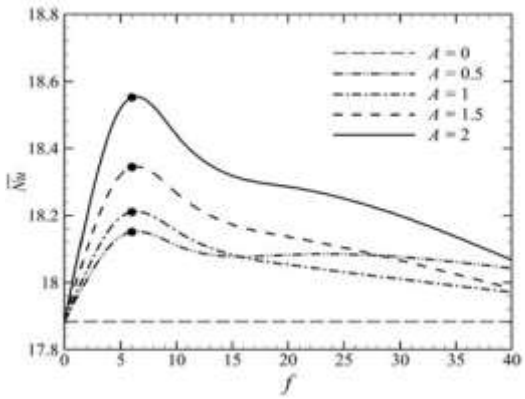

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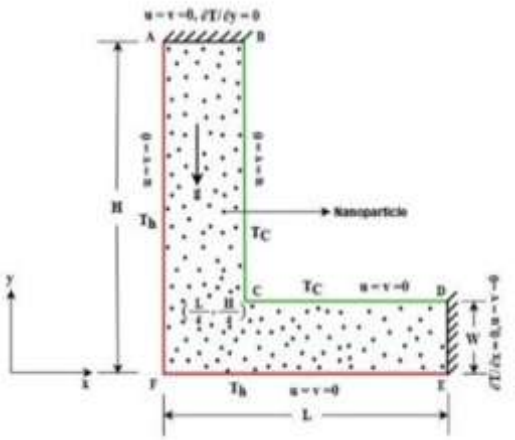
Figure 7. (a) Cavity geometry [56], (b) Effect of (f) on Nū [56]



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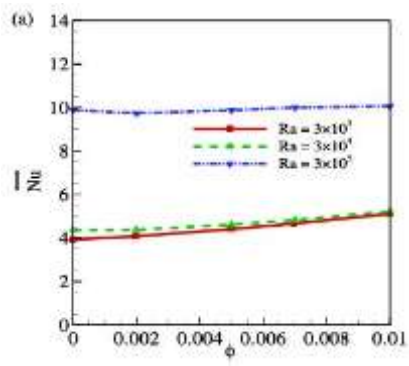

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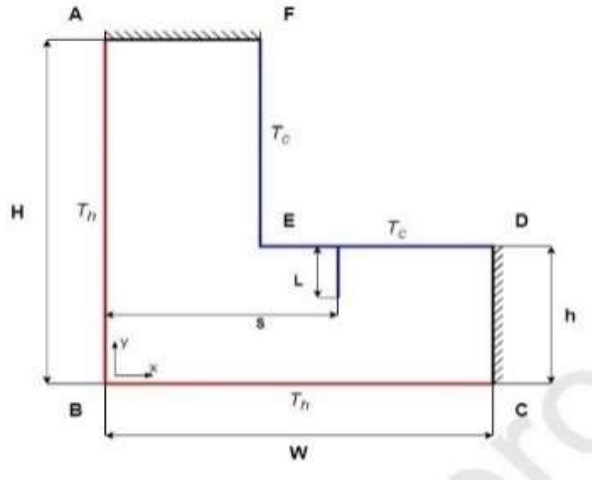
Figure 8. (a) Cavity geometry, (b) Effect of φ on Nū [57]



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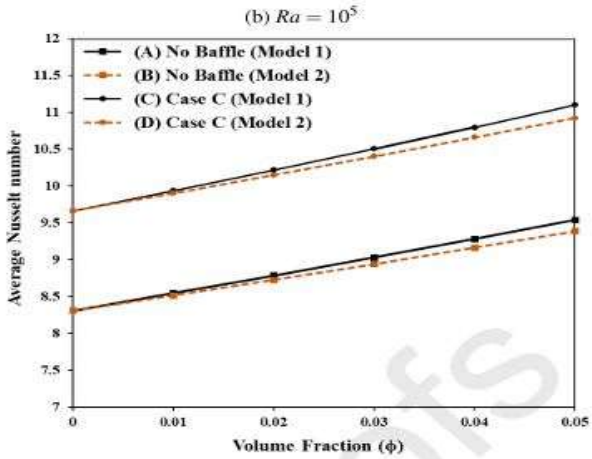
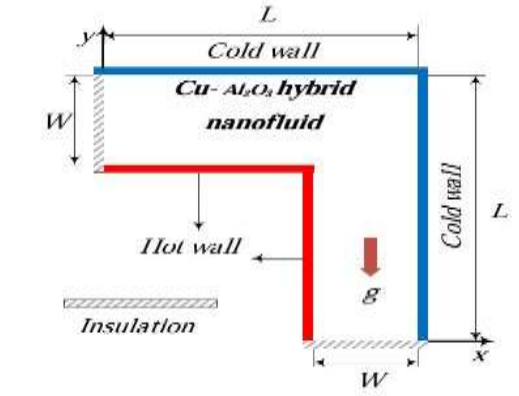


(b)

Figure 9. (a) Cavity geometry, (b) Effect of φ on Nū [58]

Ghalambaz et al. [59] investigated natural convection and entropy generation in an odd-shaped cavity as shown in Figure 10(a), governing equations solve by (GFEM). This search analyzed the effects of (Ra), (φ_{hnf}), Cu to Al_2O_3 ratio (φ_r), and width ratio (WR) on Nū. The results indicated that increased (φ_{hnf}) improved heat transfer when conduction is dominant but has less impact in convection regimes. The optimal configuration occurs at higher Ra and moderate WR, maximizing heat transfer efficiency. Moreover, entropy generation increases with Ra and φ_{hnf}, with thermal entropy dominating at low Ra and viscous entropy prevailing at high Ra. All lines are in an upward direction, indicating that the addition of nanoparticles is beneficial in all cases of this study. However, the fundamental difference is that the increase in Nū is more significant at $Ra=10^5$ as shown in the Figure 10(b).

Mahmoodi [60] used the (FVM) and the SIMPLER algorithm to couple velocity fields and pressure to evaluated the natural convection in an L-cavity. Cu/H_2O nanofluid in cavity as shown Figure 11(a), and. This research examined the effects of (φ_{hnf}), (Ra), and (AR), on fluid flow and heat transfer. The results indicate that the (Nū) increases with higher Ra and (φ_{hnf}), improved heat transfer. Furthermore, the transition from conduction to convection occurs at higher (Ra) as the (AR) decreases, meaning that reducing the (AR) delays the onset of convection. Furthermore, the heat transfer rate enhanced as the (AR) decreases, making lower (AR) L-shaped cavities more effective in convective heat transfer applications.



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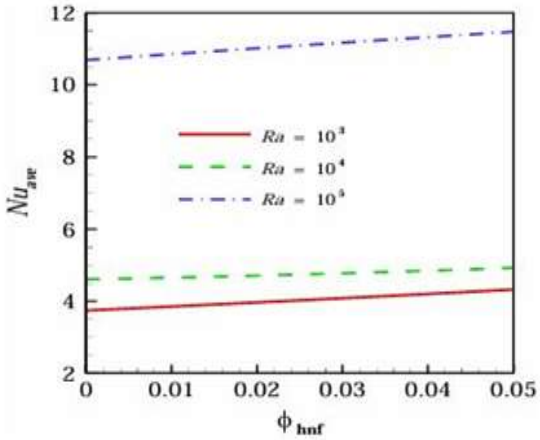

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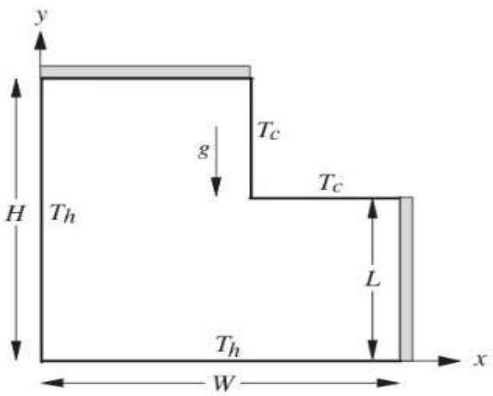
Figure 10. (a) Cavity geometry, (b) Effect of φ on Nū [59]



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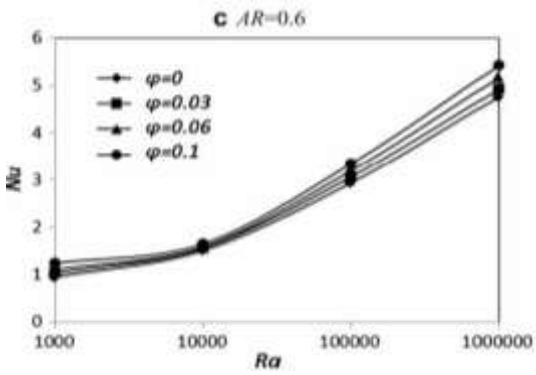


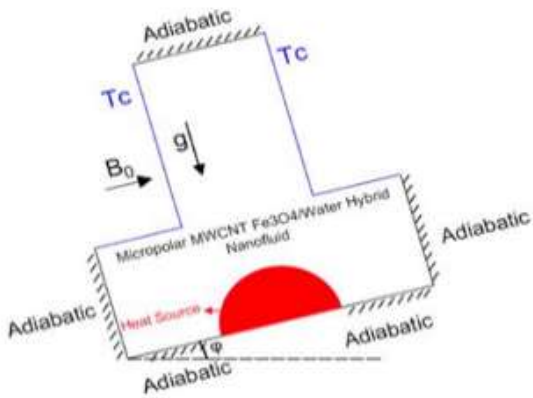
(b)

Figure 11. (a) Cavity geometry, (b) Effect of φ Nū [60]

2.3 T-shape cavity

Rahman et al. [61] used semi-circular heat source to examined (MHD) in an inclined ⊥-shaped cavity with as shown in Figure 12(a). They used the (FEM) to analyze a micro-polar MWCNT/Fe_3O_4/H_2O. Key parameters include (Ha:0-20), (Ra: 10^4-10^6), micro-rotation parameter (Γ: 0-2), and inclination of cavity (ϕ) (0°-90°). The Results showed that higher Ha and Γ reduce the (Nu), suppressing natural convection, Whereas the highest Nu (18.876) at Ra=10^6, Ha=0, Γ=0. Increasing (ϕ) to 90° lowers Nu by 24%, and a higher micro-rotation parameter (Γ=2) reduces Nu by 27%. Figure 12 shows that Nū increases with increasing Ra and reaches its highest value at Ra=10^6, while it decreases with increasing Ha. Nū having the highest value at ϕ=0° and decreasing by 24% at 90°, the use of hybrid nanofluids improved heat transfer and the highest efficiency is achieved at high Ra, low Ha and small (ϕ) as indicated (Figure 12(b)).

Askri et al. [62] examined 3D natural convection in a T-cavity. H_2O-CNT/Al_2O_3 is used. Geometry of cavity as shown in Figure 13(a), significantly affects heat transfer by modifying heat flow patterns and improved thermal performance. Increasing the size of the flanges and ribs improves buoyancy convection, increases Nū and improves heat transfer (Figure 13(b)). The (Ra) and nanoparticle concentration further amplify convection, doubling heat transfer rate at Ra=10^6 compared to pure H_2O. This study confirms that heat dissipation can be enhanced by changing the geometry of the cavity, which is an important factor in effective thermal management. Larger dimensions of T-cavity provided a greater heat exchange surface, optimizing efficiency of heat transfer.



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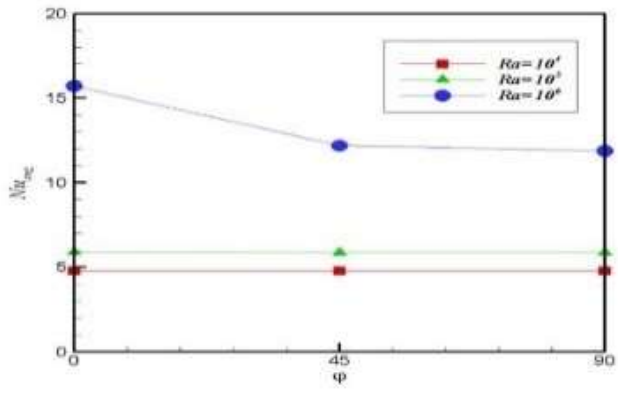
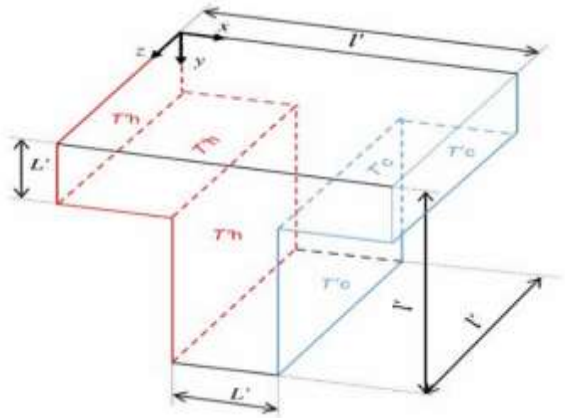
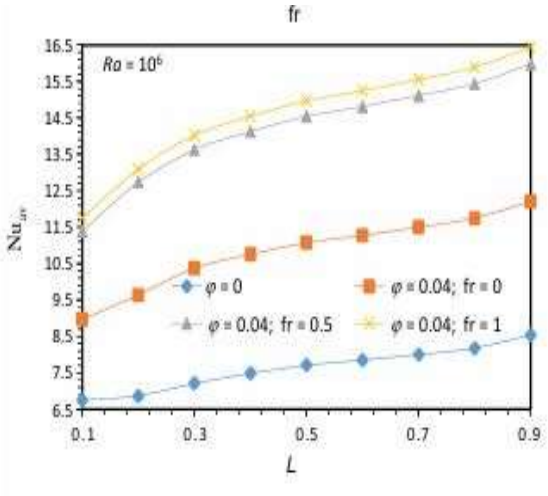


(b)

Figure 12. (a) Cavity geometry, (b) Effect of φ on Nū [61]



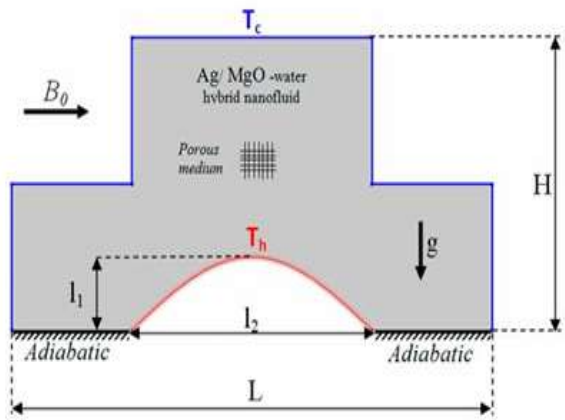
(a)



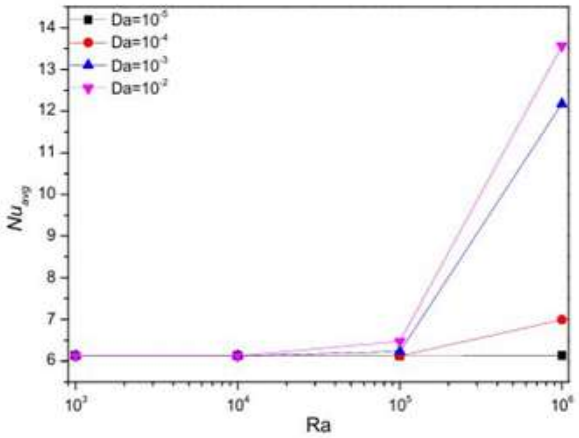
(b)

Figure 13. (a) Cavity geometry, (b) Effect of φ on Nū [62]

Abu- Libdeh et al. [63] analyzed natural convection in porous cavity. Figure 14(a) shows cavity filled with hybrid nanofluid under a constant magnetic field. The geometry of cavity significantly affects performance of heat transfer by influencing circulation of fluid, vortex formation, and generation of entropy. Increasing the (Ha) suppresses convection, reducing efficiency of heat transfer. Meanwhile, the (Da) and (Ra) enhance fluid motion, enhancing convection as shown Figure 14(b). The findings confirm that cavity geometry optimizes dissipation of heat.



(a)

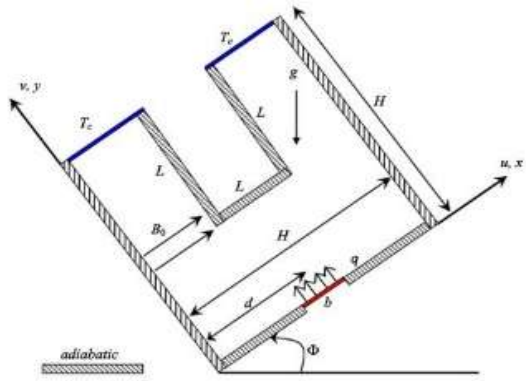


(b)

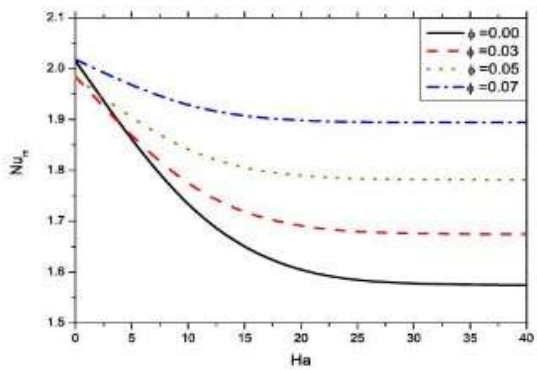
Figure 14. (a) Cavity geometry, (b) Effect of Da on Nū [63]

2.4 U-shape cavity

Nabwey et al. [64] investigated (MHD) unsteady free convection in an inclined U-cavity as shown Figure 15(a). Cu-H_2O was the nanofluid used. The cavity adiabatic vertical walls and cooled upper horizontal walls, with a discrete heat source positioned at the bottom horizontal wall. The main parameters studied include the Ha, AR, size and position of heat source, (φ), and internal heat absorption/generation. Results reveal that increasing (φ) improves convection heat transfer, while higher (Ha) and heat source length diminish the Nū as shown in Figure 15(b). This study indicated that convection is significantly suppressed by magnetic forces, which improved conduction within the Cu-H_2O filled U-cavity.



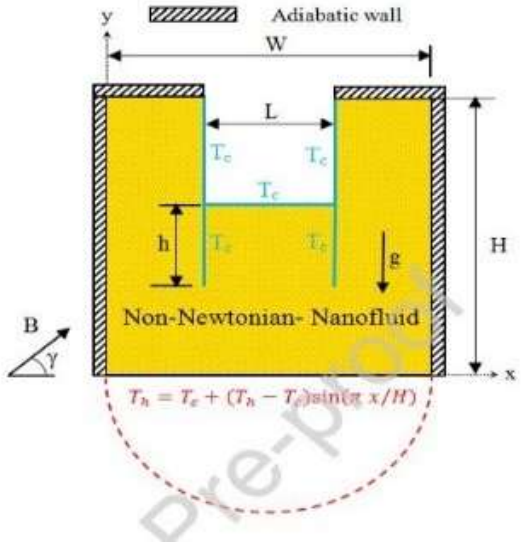
(a)



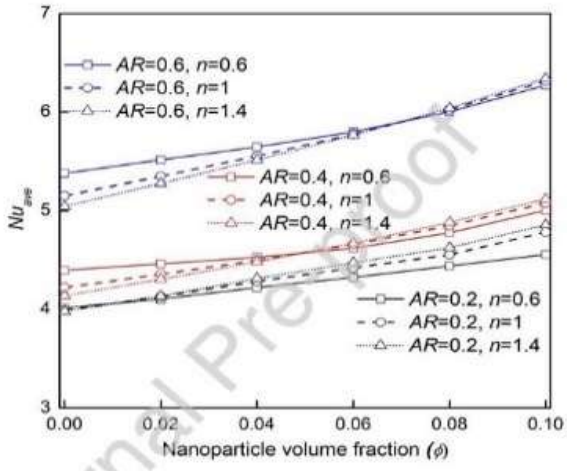
(b)

Figure 15. (a) Cavity geometry, (b) Ha effect on Nū [64]

Ali et al. [65] utilized the (GFEM) to simulate the natural convection under a magnetic field in a U-cavity. The bottom wall was heated sinusoidally, on top is the cold baffles, and sidewalls is insulated. parameters include ($Ra=10^3$-10^6), (Ha=0-50), (φ=0.0-0.09), (AR=0.2-0.6), and power law index ($0.60 \le n \le 1.4$). Results showed that higher Ra (10^6) and φ improve heat transfer, whereas Ha>30 suppresses convection due to Lorentz force. Shear-thinning fluids (n<1) enhanced heat transfer at $Ra=10^6$, and higher AR improves Nu by reducing thermal resistance. Figure 16(b) shows that the best result was at AR=0.6, $Ra=10^6$, Ha=0, and φ=0.05.

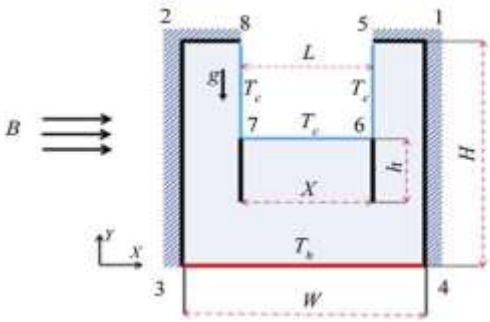


(a)



(b)

Figure 16. (a) Cavity geometry, (b) Effect of AR and φ on $N\bar{u}$ [65]



(a)

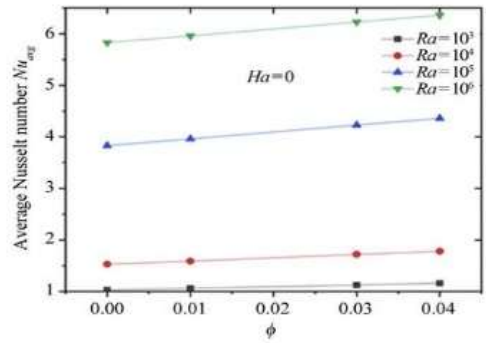
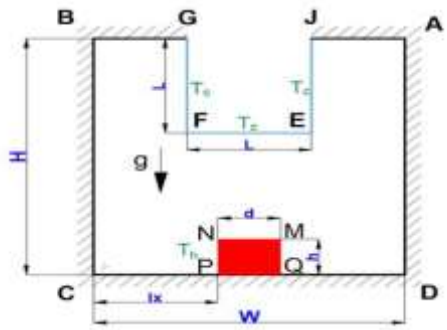


Figure 17. (a) Cavity geometry, (b) Effect of φ and Ha on $N\bar{u}$ [66]

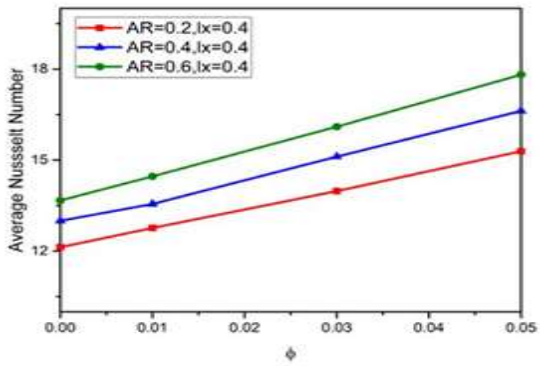
Zaim et al. [66] used the Brinkman and Wasp models to evaluate thermal conductivity of nano fluid and viscosity of nanofluid. They investigated (MHD) natural convection of Cu-H_2O in a baffled U- cavity as shown in Figure 17(a). The cavity has a cold middle baffle, insulated side walls, and heated bottom wall. parameters include ($10^3 \le Ra \le 10^6$), ($1 \le Ha \le 60$), and ($0 \le \varphi \le 4\%$). At higher Ra and φ enhanced heat transfer, while Ha > 30 suppresses convection due to Lorentz force. Ideal conditions for heat transfer occur at, low Ha, high Ra, and increased φ as shown in Figure 17(b).

Ma et al. [67] studied the natural convection of Al_2O_3/H_2O and TiO_2/H_2O in a U- cavity as shown in Figure 18(a). They analyzed numerically using the (LBM) to examine the effects of ($Ra=10^3$ to 10^6), (AR=0.2 to 0.6), and (φ=0 to 0.05) on heat transfer. Results of this research showed that increasing Ra, AR and φ as shown in Figure 18(b), Optimizes heat transfer, with Al_2O_3-H_2O nanofluid outperforming TiO_2-water. The increasing the hot obstacle height also improves heat transfer.



(a)

(d) $Ra = 10^6$

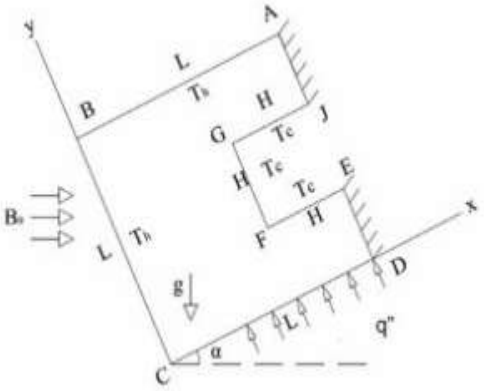


(b)

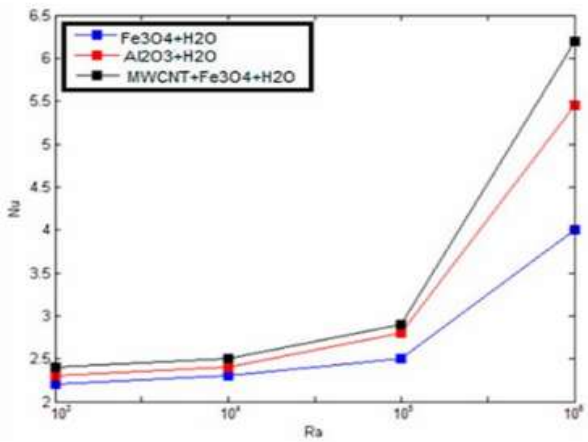
Figure 18. (a) Cavity geometry, (b) Effect of AR and φ [67]

2.5 C-E-shape cavity

Bagheri et al. [68] used (FEM) to solve natural convection in a C-cavity (Figure 19). They used the (MWCNT-Fe_3O_4-H_2O), under magnetic fields and variable heat flux. The Artificial Neural Networks with Particle Swarm Optimization is applied to Forecast the Nu. The parameters verified include (AR), (Ha), (φ), and (Ra). The (Ra) and (AR) have the effect on heat transfer, with hybrid nanofluid exceeding mono nanofluids, particularly at higher Ra values. Increasing Ha reduces efficiency of heat transfer.

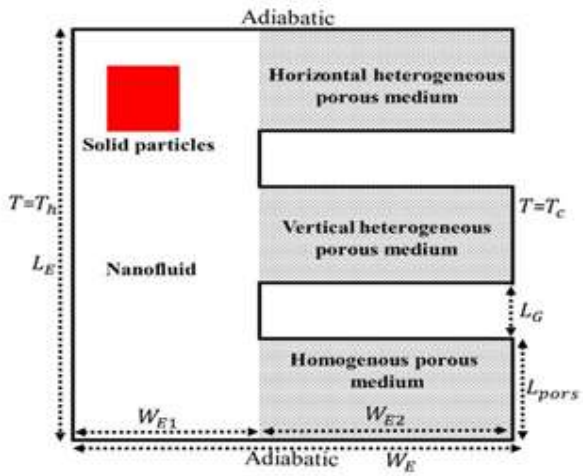


(a)

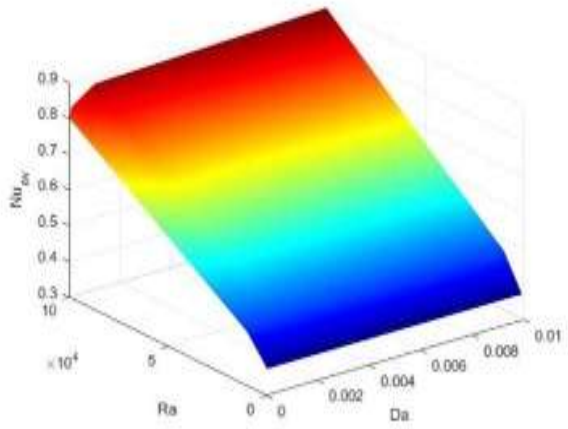


(b)

Figure 19. (a) Cavity geometry, (b) Effect of nanofluid type on Nu [68]



(a)



(b)

Figure 20. (a) Cavity geometry, (b) Effect of Ra and Da on $N\bar{u}$ [69]

Raizah et al. [69] investigated natural convection in an E-cavity filled with Al_2O_3/H_2O as shown in Figure 20(a). This research verified the effect of heterogeneous porous media and homogeneous media, nano particles with different thermal conditions, and φ (1% to 5%) on heat transfer. Ra=10^3 to 10^5) and (Da=10^{-2} to 10^{-5}) are main parameters. Figure 20(b) showed the $N\bar{u}$ increases with φ and Ra, with the highest Nu observed when the cavity is filled with horizontal heterogeneous porous media, boosting natural convection and thermal boundary layers.

3. MATH

The stander equations were used, and the fluid was considered water, and the flow was 3D-laminar, incompressible, and steady-state.

Governing Equations [70]

Mass conservation equation:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{1}$$

Momentum equations in the Cartesian Coordinates:

$$\rho_{nf}\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right) = -\frac{\partial P}{\partial x}+\mu_{nf}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right) \tag{2}$$

$$\rho_{nf}\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right) = -\frac{\partial P}{\partial y}+\mu_{nf}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right) \tag{3}$$

$$\rho_{nf}\left(u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)-\frac{\partial P}{\partial z} + \mu_{nf}\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right) \tag{4}$$

Table 1. Essential parameters in nanofluid studies

Physical Factor/Parameter	Effect	Equation	Applied in Governing Equations
Nanofluid Properties	Modify thermal and dynamic properties	ρ_nf, μ_nf, k_nf, Cp_nf	All governing equations
Hybrid Nanofluid	Combine effects of two or more types of nanoparticles	Models for k_hnf, μ_hnf	All governing equations
(Ra)	Represents ratio of buoyancy to thermal diffusion	$Ra=(g\beta\Delta TH^3)/(\alpha\nu)$	Non-dimensional analysis
(Ha)	Quantifies magnetic field influence on flow	$Ha=B\cdot L\cdot\sqrt{(\sigma/\mu)}$	Momentum equation via Lorentz force
Porous Medium	Adds flow resistance due to porous material	$-\mu_{nf}\cdot u/K$	Momentum equation
Buoyancy Force (Boussinesq Approx.)	Represents thermal buoyancy effect	$\rho_{nf}\cdot g\cdot\beta_{nf}\cdot(T - T_0)$	Momentum equation
Lorentz Force	Represents magnetic damping effect	$-\sigma\cdot B^2\cdot u$	Momentum equation
Thermal Boundary Conditions	Simulates realistic thermal boundaries	T=constant, or function like sin(x)	Energy equation/boundary conditions

Heat transfer equation:

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=\alpha_{nf}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right) \quad (5)$$

Table 1 summarizes the main physical factors involved in numerical studies of nanofluids and hybrid nanofluids. It includes the effect of each factor, the typical equation used to model it, and the part of the governing equations where it is applied.

4. CONCLUSIONS

i. Most of the studies conducted were numerical, and there is a scarcity of their application in reality, which gives a greater incentive to use them experimentally and benefit from them.
ii. Classical cavities such as rectangles, squares, etc. are symmetrical and will produce uniform heat flow patterns, while complex cavities are characterized by sharp asymmetry, which leads to the generation of complex vortices and hot spots.
iii. There is a very scarcity in verifying transitional and turbulent states, as most research has focused on the laminar state, which can make this point a scientific gap in research.
iv. Most existing studies rely on fixed boundary conditions, which often do not reflect the real reality, leading to noticeable errors when compared with experimental results.
v. The hybrid nanofluid is also a promising option with literal shaped cavities as it enhances heat transfer more compared to the nanofluid.
vi. The effect of porous medium or the magnetic flux did not differ significantly from the effect in classical shaped cavities.
vii. Cavities with sharp edges and complex angles (such as H and L) may promote the formation of thermal vortices that increase the natural convection. Efficiency.
viii. Complex cavities provide better control over the distribution of thermal currents than conventional cavities (square and rectangular).
ix. The H-geometric cavities with a porous medium improved the (Nu) value by an increase of 60%.
x. Different fluids were used (water, nanofluid, hybrid nanofluid), and no specific fluid type showed superiority in enhancing the (Nu) over the other types.

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NOMENCLATURE

B	dimensionless heat source length
CP	specific heat, J. kg^{-1}. K^{-1}
g	gravitational acceleration, $m.s^{-2}$
k	thermal conductivity, $W.m^{-1}$. K^{-1}
Nu	local Nusselt number
Ha	Hartmann number
h	the partition's height, m
P	Pressure, N/m2
Pr	Prandtl number
Ra	Rayleigh number
T	Temperature, k
t	Time, s
u	the x-direction velocity component, m/s
v	the y-direction velocity component, m/s
w	the z-direction velocity component, m/s
x	the coordinate's horizontal component, m
y	the coordinate's vertical component, m
z	the axial direction coordinate, m
AR	Aspect ratio
Da	Darcy numbers

Greek symbols

α	thermal diffusivity, m^2. s^{-1}
β	thermal expansion coefficient, K^{-1}
φ	solid volume fraction
μ	dynamic viscosity, kg. $m^{-1}s^{-1}$
ρ	Density (Kg/m3)
θ	Cavity's inclination angle (º)
ϕ	Side wall Inclination angle (º)

Abbreviations

CFD	Computational Fluid Dynamic
CVM	Control Volume Method
FDM	Finite Difference Method
FEM	Finite Element Method
FVM	Finite Volume Method
LBM	Lattice Boltzmann Method
MRT	Multiple Relaxation Time
PIV	Particle Image Velocimetry
Rd	Radiation number
2D	Two-dimensional
3D	Three-dimensional
MHD	Magnetohydrodynamics
TEG	Total Entropy Generation

Subscripts

b	Block
c	Cold
E	External
eff	Effective
f	Fluid
I	Internal
L	Length
hnf	Hybrid Nano fluid
nf	Nano fluid
s	Solid particle