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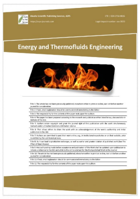

Investigation of fluid flow and heat transfer for an optimized lid driven cavity shape under the condition of inclined magnetic field

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Abstract: Fluid flow in the lid driven cavity is a well-known phenomenon in the realm of fluid flow and heat transfer. Different cavity shapes such as square, circular, trapezoidal, and hexagonal have already been studied. However, most of the parametric analyses have previously been done using one specific cavity shape design. The present study intends to generalize the cavity design for a larger range of applications starting from the selection of cavity form due to the enhancement of heat transfer inside that selected cavity for different boundary conditions. Numerical studies using a finite element solver have been carried out to investigate the physics of fluid flow and heat transmission in a cavity where a wall of the enclosure is moving. In this research, the average Nusselt number for six distinct shaped lid-driven cavities is studied (e.g., square, rhombus, circular, rounded rectangular, trapezoidal and hexagonal). The hexagonal-shaped cavity has the largest Nusselt number of all of them. The heat transfer increases by about 90% when the cavity shape changes from square to hexagonal at Ri = 0.1, Pr = 7, Re = 100, Ha = 30, and $\gamma = 60°$. To boost the heat transfer rate, magnetohydrodynamics (MHD) mixed convection in a lid-driven cavity with an imposed angled magnetic field was investigated. Richardson number, Reynolds number, Prandtl number, Hartmann number, and magnetic inclination angle within the enclosure are shown in terms of streamline plots, isothermal contour profiles, and Nusselt number. Through parametric investigations of cavity shapes, inclined magnetic fields, and other boundary conditions, the current research intends to improve the Nusselt number within the cavities.

1 Introduction

Heat transfer improvement is one of the vital studies in recent days because of the technological advancement. Researchers have already investigated fluid flow and heat exchange in a variety of situations and phenomena. The area of convective heat transfer arose from major technical endeavours such as aviation, energy conversion, and extra-terrestrial space exploration (Bejan, 2013). Natural convection occurs as a result of buoyancy or gravitational force flow, whereas forced convection occurs as a result of shear flow caused by any wall movement in the enclosure. Mixed convection flow occurs in any cavity as a result of the accumulation of free and forced convection within the cavity. Convection caused by buoyancy in porous media saturated with fluid has sparked significant research interest for their extensive engineering applications such as oil recovery, aquifer management, nuclear waste disposal, metal casting (alloy solidification),

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building thermal insulation, etc. (Vafai & Hadim, 2018).(Krakov, Nikiforov, & Materials, 2002) studied free convection in a square enclosure with an even outside magnetic field.Because of its significance on thermal efficiency, laminar free convection in cavities has gotten a lot of attention in the last few decades in many engineering applications such as heat transfer in various electronic equipment, furnaces, ovens, solar collectors, etc. pointed out by (Saeid & Yaacob, 2006). (Tuckerman & Pease, 1981) investigated that forced convection can be used to cool the hot surface of devices. For various scientific, engineering, and biological applications, such as system cooling, lubrication technology, drying technologies, and food processing, mixed convection has attracted the researcher (Al-Amiri, Khanafer, & Pop, 2007; Billah et al., 2011).

In recent times, Convective heat transmission in a lid driven cavity has drawn the attention of researchers because heat is transmitted significantly in such modifications. A lid driven cavity means there are one or more moving walls inside the chamber. Heat transfer increases remarkably because Reynold's number is associated with this. (Khanafer, Al-Amiri, & Pop, 2007) studiedunstable mixed convection in a driven enclosure by employing an outwardly stimulated slithering lid. (Rahman, Mamun, & Saidur, 2011) investigated a lid-driven cavity with a square block with MHD mixed convection and joule heating. (Alleborn, Raszillier, Durst, & Transfer, 1999) investigated the arrangement of stable two-dimensional flow along with heat and mass transport in a little depth lid driven cavity with a moving heated lid and a moving cooled lid numerically. (Munshi, Mostafa, Munsi, & Waliullah, 2018) studied the hexagonal chamber with a corner heater, operated by the lid in the hydrodynamic mixed convection condition. They noted that this issue can arise for many engineering purposes including heating and cooling flows in buildings, as well as elevators, escalators, and conveyor belts. (Sivasankaran, Malleswaran, Lee, Sundar, & Transfer, 2011) carried out research on Hydro-magnetic integrated convection where the sidewalls are sinusoidal and driven by the lid. (Dawood & Teamah, 2012) examined a square lid driven cavity with dual diffusive hydro-magnetic mixed convection. (Moallemi, Jang, & Transfer, 1992) shows how the Prandtl number influences a lid driven enclosure on laminar mixed convection heat transfer. (Oztop, Al-Salem, Pop, & Transfer, 2011) studied the enclosure with a corner heater that is controlled by the lid under the conditions of magnetohydrodynamics mixed convection.

The magnetic field's presence inside an enclosure causes remarkable alterations in fluid flow and heat transmission. Magnetic field changes thermal and energy systems significantly (Rudraiah, Barron, Venkatachalappa, & Subbaraya, 1995). Liquid metals are heated, pumped, stirred, and levitated using magnetic fields in industries (Ahmad Dar & Elangovan, 2016). (Bakar, Roslan, Karimipour, & Hashim, 2019) noted that the physical presence of a fluid flow problem stimulated by an inclined magnetic field and its implementation includes the construction of magnetohydrodynamics power generators, pumps, and accelerators. In the medical industry, the inclined magnetic field uses for magnetic resonance imaging (MRI) and to diagnose various diseases. They also discovered that, because the MHD field slows the flow of the fluid and minimizes heat transmission in the enclosure, increasing the inclination magnetic angle in the MHD field enhances fluid flow. (Bakar et al., 2019) as well examined that when there is a magnetic field, it retarded the mixed convection flow, the average Nusselt number is increasing by the increase of magnetic field angle, and increase of the Richardson number leads to a reduction in heat transfer. (Nasrin, Parvin, & Transfer, 2011) investigated many industrial uses exist for the electrically conducting fluid in the presence of the magnetic field for the free and forced convection both including geothermal reservoirs, nuclear reactor cooling, thermal insulations, and petroleum reservoirs. They also mentioned that similar issues can develop during the operation of electronic packages and microelectronic devices. (Sud, Sekhon, & Mishra, 1977) researched on how a magnetic field exerts a pumping action on the blood and they discovered that blood velocity can be enhanced by the suitable magnetic field.

The current research focuses on the effect of different cavity shapes with the same boundary conditions and finding out the optimum cavity shape for maximum heat transfer rate that can be used for different engineering applications. Further research has been done to see how the magnetic field affects the system in free, forced, and mixed convection with the optimum shaped cavity. The result has been shown in terms of streamline plot, isothermal contour, and Nusselt number for a different dimensionless number such as Hartmann Number, Richardson Number, Reynolds Number, and Prandtl Number. The current study of a lid-driven optimized shaped enclosure with the inclined magnetic angle will benefit biomedical research, pharmaceutical industries, nuclear physics, and the food industry, as well as the development of various engineering machinery such as heating systems, exchangers, and coolers, among other fields.

2. Problem Description

Six distinct shaped cavities have been studied with identical boundary conditions as illustrated in figure 1: square, rhombus, circular, rounded rectangular, trapezoidal, and hexagonal. The top walls heat the cavities, while the bottom walls are cooler than the top walls. The rest of the walls are kept at an adiabatic temperature.

The upper walls are shifting in the x-direction, and all of the cavities are subjected to an inclined magnetic field. To make a better comparison, the total cavity area and the length of the hot top walls and cold bottom walls are kept the same for all the cavities. With the inclined magnetic angle, the lid-driven cavities are examined in free, forced, and mixed convection. The cavities are containing only pure fluid, and the system is affected by the imposed magnetic fields.

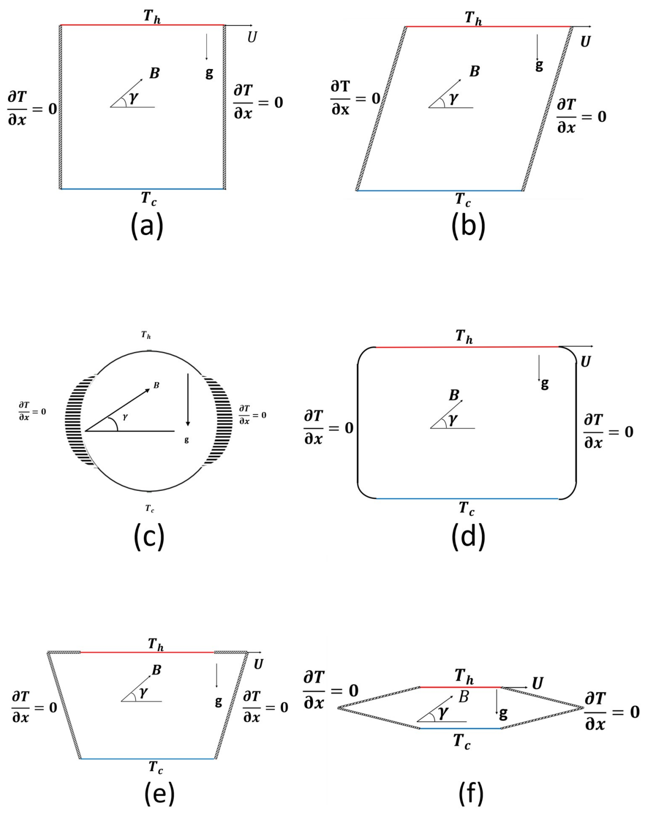


Fig. 1. Physical configuration of the cavities.

2.1 Governing Equations & Numerical Solutions

The operating fluid is incompressible and Newtonian. The flow is two-dimensional, laminar, and continuous in the enclosures. The induced temperature-independent magnetic field imposed by the external magnetic field was considered. The effect of viscosity dissipation and joule heating of the fluid are also insignificant. When the density difference in the other thermo-physical parameters and the buoyant term of the field is considered to remain the same, the Boussinesq approximation holds valid (Bejan, 2013). The following are the dimensional forms of the continuity, momentum, and energy equations (Bakar et al., 2019):

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

$$\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=-\frac{1}{\rho}\frac{\partial p}{\partial x}+v\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)+\frac{B_0^{\,2}\sigma}{\rho}(v\sin\gamma\cos\gamma-u\sin^2\gamma) \tag{2}$$

$$\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{1}{\rho}\frac{\partial p}{\partial y}+v\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\frac{B_0^{\,2}\sigma}{\rho}(u\sin\gamma\cos\gamma-v\cos^2\gamma)+g\beta(T-T_c) \tag{3}$$

$$\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \tag{4}$$

The dimensionless governing equation can be written as,

$$\frac{\partial U}{\partial x}+\frac{\partial V}{\partial y}=0 \tag{5}$$

$$\left(U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}\right)=-\frac{\partial p}{\partial x}+\frac{1}{\mathrm{Re}}\left(\frac{\partial^2 U}{\partial x^2}+\frac{\partial^2 U}{\partial y^2}\right)+\frac{Ha^2}{\mathrm{Re}}(V\sin\gamma\cos\gamma-U\sin^2\gamma) \tag{6}$$

$$\left(U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}\right)=-\frac{\partial p}{\partial x}+\frac{1}{\mathrm{Re}}\left(\frac{\partial^2 V}{\partial x^2}+\frac{\partial^2 V}{\partial y^2}\right)+\frac{Ha^2}{\mathrm{Re}}(U\sin\gamma\cos\gamma-V\cos^2\gamma)+\frac{Gr}{\mathrm{Re}^2}\theta \tag{7}$$

$$\left(U\frac{\partial \theta}{\partial X}+V\frac{\partial \theta}{\partial Y}\right)=\frac{1}{\mathrm{Re}\,\mathrm{Pr}}\left(\frac{\partial^2 \theta}{\partial X^2}+\frac{\partial^2 \theta}{\partial Y^2}\right) \tag{8}$$

Where, U & V the velocity components in X & Y directions, The dimensionless parameter have been used $\mathrm{X}=\mathrm{x}/\mathrm{L}$,

$$Y = y/L,\quad U = \frac{uL}{\alpha},\quad V = \frac{vL}{\alpha},\quad \theta = \frac{T - T_h}{T_h - T_c}\quad P = \frac{(p + \rho g y)L^2}{\rho v^2}$$

In fluid mechanics and heat transfer, the variables have their usual significance. The governing parameters are:

$$Re = \frac{U_0 L}{v},\quad Ha = BL\sqrt{\frac{\sigma}{\rho v}},\quad Pr = \frac{v}{\alpha},\quad Gr = \frac{g\beta(T_h - T_c)}{v^2}$$

The boundary conditions of the cavity are:

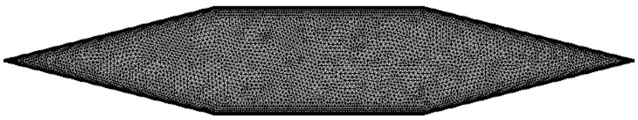
On the top wall, $u = u_0$, $v = 0$, $T = T_h$

On the bottom wall, $u = 0$ $v = 0$, $T = T_c$

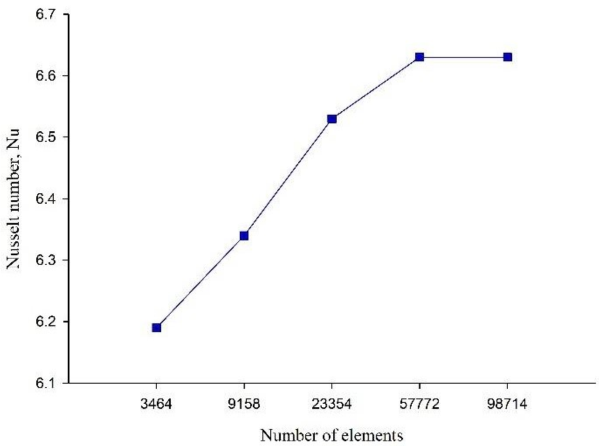
On the left and right side walls, $u = 0$, $v = 0$, $\frac{\partial T}{\partial x} = 0$

The nusslet number can be defined as, $Nu = -(\frac{\delta\theta}{\delta X})$

The governing equations with described boundary conditions were solved using the finite element method. The isothermal contours and Nusselt number inside the cavities are shown using COMSOL Multiphysics 5.5 finite element solver. The simulations are done using triangular meshing as shown in Figure 2(a). As seen from figure 2(b), the variation of the nusselt number is very negligible for altering the number of elements 98714 from 23354. However, the present study considers the higher number of elements to get a better visualization of the reported results.



(a)

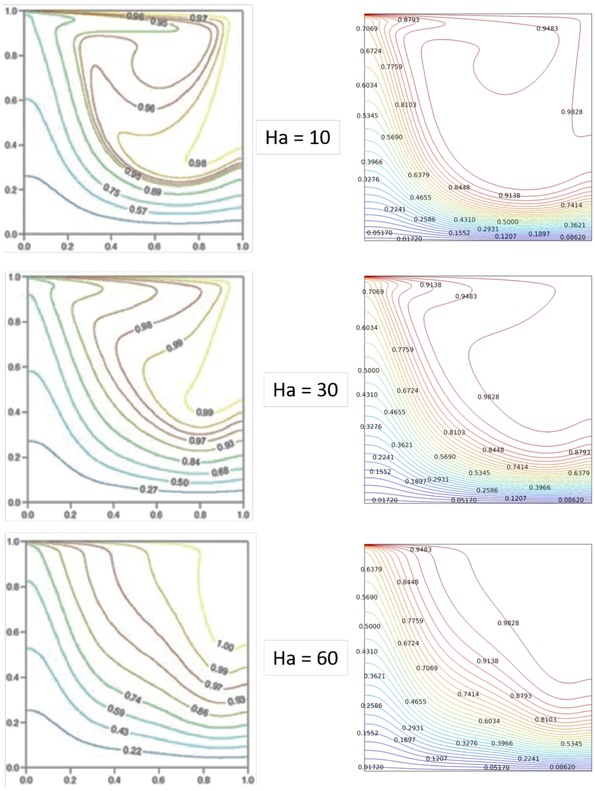


(b)

Fig. 2. (a) Meshing of the computational domain (b) Grid independency test.

3. Validation of the numerical model

The case has been studied for mixed convection with an inclined magnetic field in a lid-driven cavity. From the literature (Bakar et al., 2019), the parameters have been taken and figure 3 indicated an almost similar pattern of isotherms with the available literature. Figure 4 shows the average deviation of the reported Nu value is found to be 6.25%.



(Bakar et al., 2019) (Present study)

Fig. 3. Comparison of isotherms with those of (Bakar et al., 2019) and present result while Ri = 0.1, Re = 100, Gr =10^3, γ = 90° and different Hartmann number.

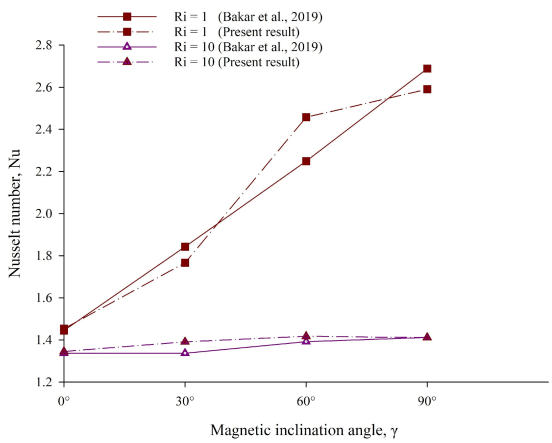


Fig. 4. Nusselt number along the top wall (hot wall) for different value of magnetic inclination angle γ while, Ha = 30, Re = 100, Pr = 7.

4. Results

4.1 Effect of different cavity shapes

Isothermal contours for six different shape cavities has been plotted for Ri = 1, Re = 100, Pr = 7 and magnetic inclination angle, γ = 60° at figure 5. As Ri = 1, It indicates pure mixed convection. As the top wall is hot and lid-driven, fluid is transposing from the hot top wall to the cold bottom wall.

Figure 6 depicts that Nu decreases as the Ri increases because free convection dominant over forced convection for the higher value of Richardson number. Among the shapes, the hexagonal shape cavity shows the higher Nusselt number.

The Prandtl number (Pr) represents the ratio of momentum to thermal diffusivity. Figure 7 depicts how the Pr number influences the heat transmission mechanism. As Pr number is a fluid property, it will surely control the flow dynamics inside the cavity. For large values (Pr >> 1) of Pr number, the momentum diffusivity dominates the flow behavior indicating the heat convection is more significant compared to conduction. However, convection is very effective in transferring energy. The simulation has been done for the different Pr numbers by altering the value ranging from 0.71 to 7.

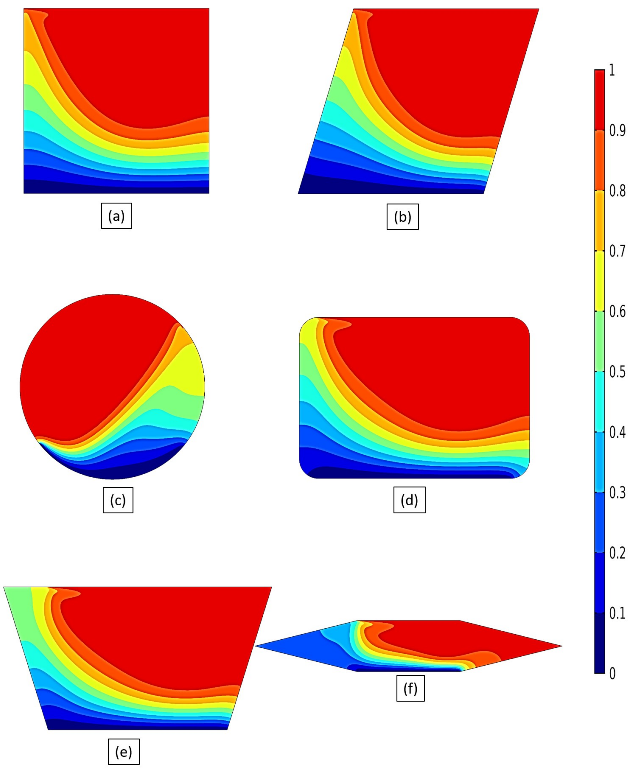


Fig. 5. Isothermal contour for Ri = 1 with Re = 100, Pr = 7, Ha = 30, and magnetic inclination angle γ = 60°.

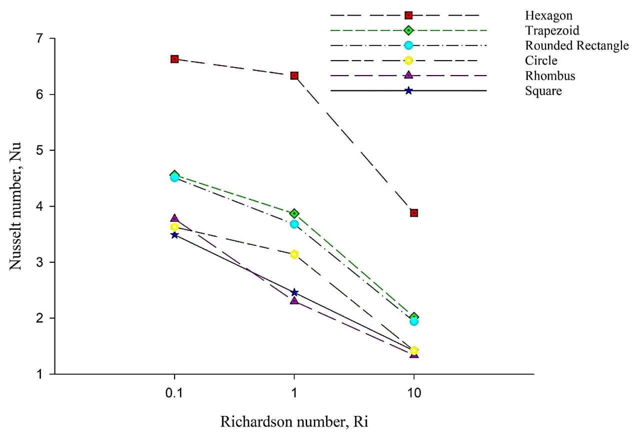


Fig. 6. Nusselt number along the top wall (hot wall) for different shape cavity with Ri = 0.1,1, 10, Ha = 30, Re = 100, Pr = 7, and γ = 60°.

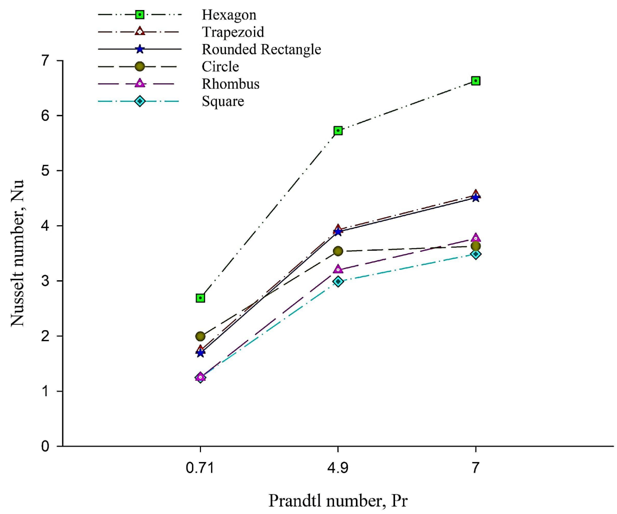


Fig. 7. Nusselt number along the top wall (hot wall) for different values of Prandtl Number at Ri = 0.1, Re = 100, Ha = 30, magnetic inclination angle, *γ = 60°* indifferent shape cavity.

Figure 7 shows that, as the Prandtl number rises, Nu also increases in the cavity. So, more heat is exchanged from the hot wall to the bottom wall. However, the cavity shape effect is quite visible under the same boundary conditions. Around 90% increment of Nu is observed at Pr = 7 for changing the cavity shape to hexagonal from the square.

Hence, the present study considers hexagon cavity as the main design parameter for cavity shape. Further parametric studies are conducted on this shape of the cavity to observe the effect.

4.2 Effect of aspect ratio, AR on Nu number

Figure 8 shows the isothermal contour for different aspect ratios (ratio of base length and height). Temperature gradient decreases when the height difference increases

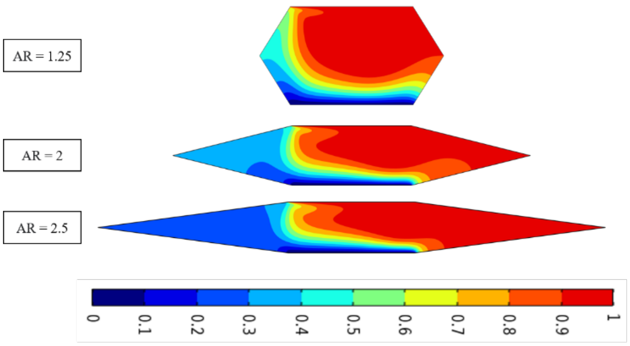


Fig. 8. Isothermal Contour for aspect ratio, AR = 1.25, 2, 2.5 with Ha = 30, Ri = 0.1, Pr = 7 and magnetic inclination angle γ = 60°.

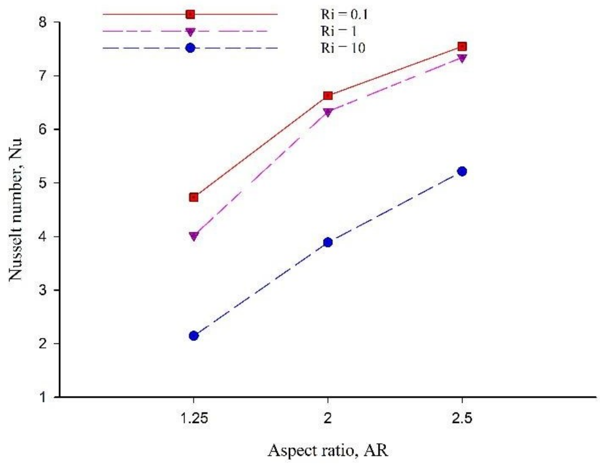


Fig. 9. Nusselt number along the top wall for different value of aspect ratio with Ri = 0.1,1,10 Ha = 30, Pr = 7, magnetic inclination angle γ = 60°.

between the hot wall and cold wall. AR = 2.5 shows the highest Nu number compared to others. As the aspect ratio increases, the distance betwixt the hot top wall and the cold bottom wall is decreasing resulting increase in temperature gradient and respective heat transfer.

Figure 9 shows the higher Nu number can be obtained from the higher aspect ratio of the enclosure because the hot wall and cold wall would be close to each other causing better heat transmission. The Nu number rises with the rise of the aspect ratio.

However, for further study, the present research considers an aspect ratio (AR) of 2.

4.3 Effect of Richardson Number, Ri on Nu number

The non-dimensional number that indicates the proportion of the buoyancy term to the flow shear term is known as the Richardson number. The Richardson number is used to analyze density and convection currents in reservoirs and oceans, as well as to forecast weather, among other things.

The magnetic field at 60° inclination angle has been applied in figure 10. The average value of the Nusselt number along with the hot wall decrease as the Richardson number increases. As from the definition, $R_i=Gr/Re^2$ when the Reynolds number is constant, the Richardson number is increasing means the Gr number (the proportion of a fluid's buoyancy and its viscous force) is also increasing. So, free convection is replaced by forced convection when Ri decreases. At Ri = 0.1 indicates forced convection, mixed convection is presented by Ri = 1.0, and free convection is specified by Ri = 10. For a lower value of Ri, the flow velocity inside the cavity increases since the forced convection occurs by the movement of the lid wall. Hence, the temperature gradient decreases (less red region) with the increment of Ri, and so the hot wall transmits less heat to the cold wall as observed in Figure 10.

Recirculating vortices are observed in the center of the enclosure because the top wall is moving towards the x-direction (as shown in Figure 11). The strength of core vortexes decreases and shifts to some weak vortices at the two extreme corners of the cavity when the Richardson number is increased to 10. Hence, free convection is dominant for the higher value of Ri, as a result, heat transfer is reduced.

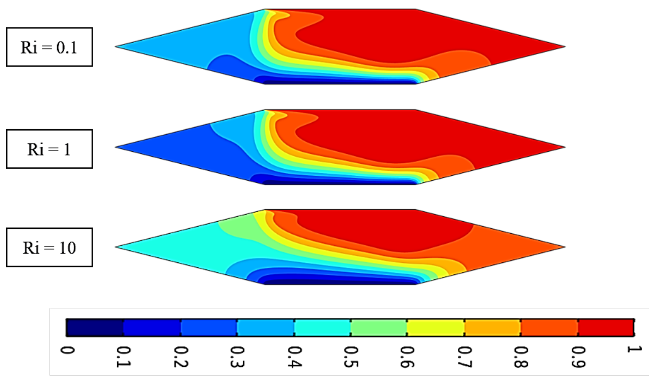


Fig. 10. Isothermal contour for Ri = 0.1,1,10 with Re = 100, Pr = 7, Ha = 30, and magnetic inclination angle γ = 60°

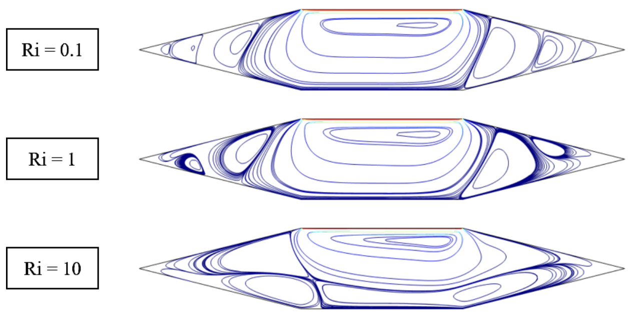


Fig. 11. Streamlines for Ri = 0.1, 1, 10 with Re = 100, Pr =7, Ha = 30 & magnetic inclination angle γ = 60°.

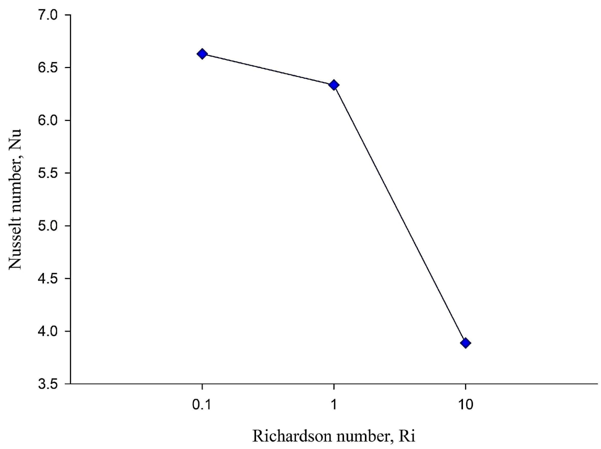


Fig. 12. Nusselt Number along the top wall for Ri = 0.1, 1, 10 at Re = 100, Ha = 30, Pr = 7, magnetic inclination angle γ = 60°.

It is observed in Figure 12 that when the Richardson number is increasing, the Nusselt number drops. Nu decreases very less when Ri increases to 0.1 to 1. But there is a significant decrease in Nu for Ri = 10 which indicates free convection.

4.4 Effect of Hartmann Number, Ha on Nu number

Magnetohydrodynamics (MHD; alternatively magneto-fluid dynamics or hydro-magnetics) is the investigation of electrically conducting fluid's (for example plasmas, electrolytes, liquid metals) magnetic properties. In a moving conductive fluid, magnetic fields can induce currents. MHD is characterized by a set of equations combining Maxwell's equations for electromagnetism and Navier–Stokes equations for fluid dynamics. The Hartmann number (Ha) is used to quantify the consequence of the magnetic field which is the proportion of magnetic force and fluid's viscous force. Figure 13 depicts Isothermal contour for different Hartmann number at Re = 100, Pr = 7, Ri = 0.1, and γ = 60°. As the Hartmann number increases, it tells about the magnetic strength increment inside the cavity. The absence of a magnetic field at Ha equal to zero, allows for free or forced convection, depending on the Ri number. Figure 13 shows that when the magnetic field's effects in the cavity increase (raising the Ha number), the conduction mode of heat transfer takes precedence over convection, lowering the Nu number.

The streamline contour in Figure 14 shows that without the magnetic field effect (Ha = 0), six circulation cells have been created. The center vortex is rotating clockwise due to the lid effect. The other vortexes in the left corner are rotating anticlockwise. The vortex right to the center vortex is rotating anticlockwise. When the Ha increases to 10 from 0, a similar type of pattern is seen with the decrement of core vortex size depicting the strength reduction of convection currents. As a result, as the number of Ha increases, the thermal gradient, and Nu decrease.

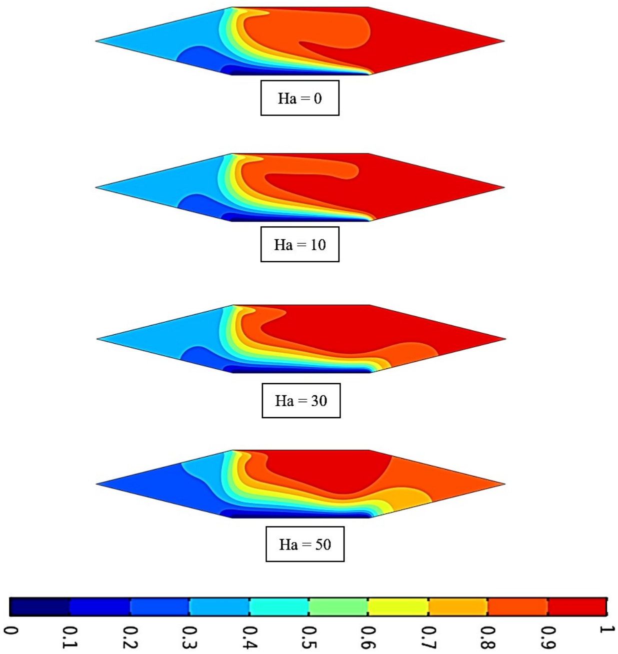


Fig. 13. Isothermal Contour for Ha= 0, 10, 30, 50, at Re = 100, Ri = 0.1, Pr = 7 and magnetic inclination angle γ = 60°.

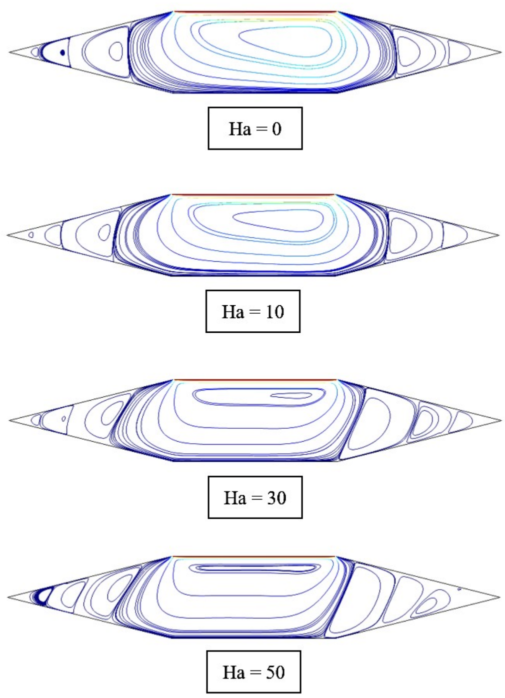


Fig. 14. Streamlines for Ha = 0, 10, 30, 50 at Re = 100, Ri = 0.1, Pr = 7 and magnetic inclination angle, γ = 60°.

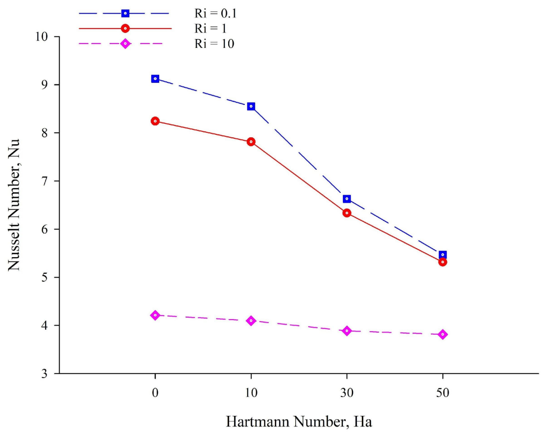


Fig. 15. Nusselt number along the top wall for different value of Hartmann number at Ri = 0.1, 1, 10, Pr = 7 and magnetic inclination angle γ = 60°.

The Nusselt number drops as the magnetic field strength increases as shown in Figure 15. The magnetic field has little effect on the higher values of the Richardson Number as observed for the variation of Nu number values at Ri = 10 due to the dominance of free convection over the conducting fluid's conduction effect.

As Ri decreases, heat transfer enhances, however, due to the magnetic field's existence, the conduction dominates over the forced convection resulting in a gradual decrease of Nu for lower Richardson number.

4.5 Effect of Magnetic Inclination angle, γ on Nu number

The temperature gradient decreases gradually with the increase of magnetic inclination angle. The magnetic field's inclination angle influences the flow field and thermal distribution as observed in Figure 16.

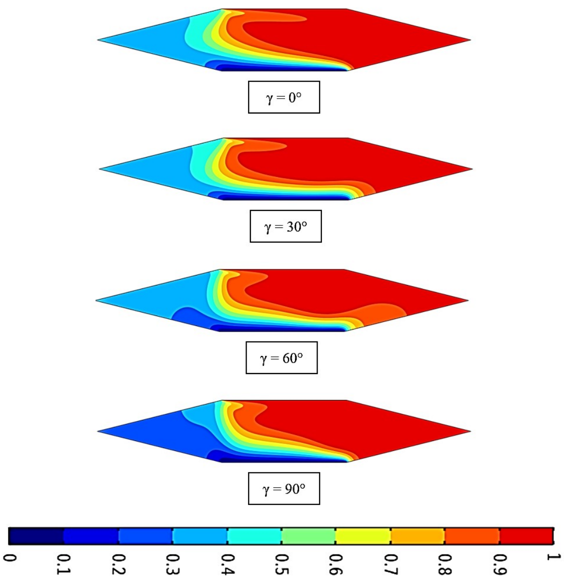


Fig. 16. Isothermal Contour for different value of magnetic inclination angle, γ with Ri = 0.1, Ha = 30, Pr = 7, Re = 100.

From Figure 17, at Ri = 10, the decrease in Nu number is very small compared to Ri = 0.1 and Ri = 1. However, the Nusselt number decreases with the increase of magnetic inclination angle at aspect ratio, AR = 2. The distance between the hot top wall and the cold bottom wall shrinks as the aspect ratio rises. So, heat is mostly transported through conduction rather than convection. For this reason, heat transmission slows progressively when a magnetic field with an inclination angle is imposed on it.

Figure 18 illustrates that at aspect ratio = 1.25 of the cavity, the value of Nu increases for Ri = 0.1 and Ri = 1. Nu is almost constant for Ri = 10 when the aspect ratio is 1.25. The hot top wall and the cold bottom wall move away when the cavity's aspect ratio drops, favoring convection over conduction. As a result, when Ri = 0.1 and 1 and the aspect ratio is 1.25, Nu rises as the magnetic inclination angle rises. As Ri = 10 indicates strong free convection,

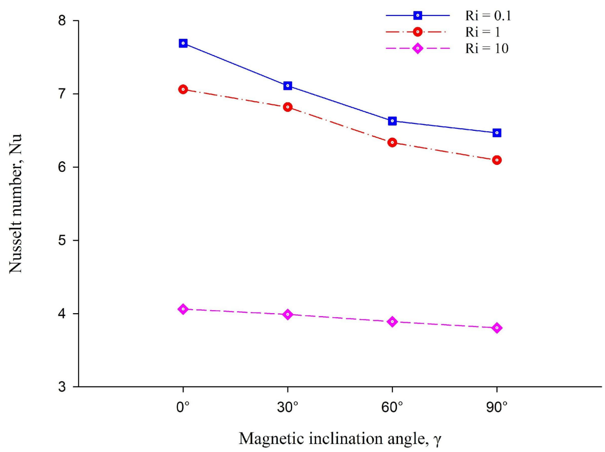


Fig. 17. Nusselt number along the top wall for different value of magnetic inclination angle, γ with Ri = 0.1,1,10, Ha = 30, Pr = 7, Re = 100, AR= 2.

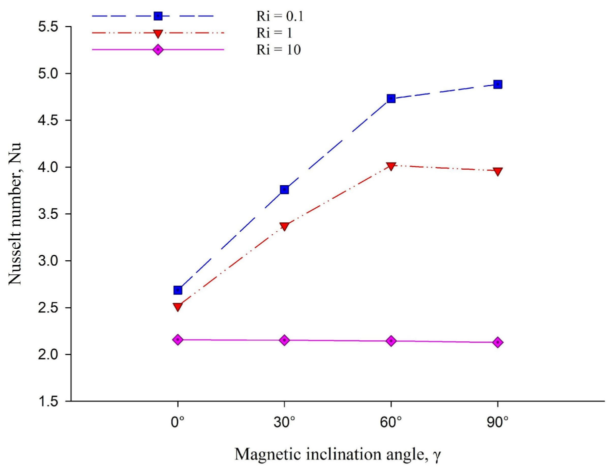


Fig. 18. Nusselt number along the top wall for different value of magnetic inclination angle, γ with Ri = 0.1,1,10, Ha = 30, Pr = 7, Re = 100, AR = 1.25.

magnetic inclination angle have no significance on the results. Hence, AR of the cavity is playing a very important role in determining the flow physics as observed from both Fig. 17 and Fig. 18.

4.6 Effect of Reynolds number, Re on Nu number

As when Re is increased, there is strong forced convection. The velocity of the fluid within the enclosure is increased for a higher value of Reynolds number. Fluids move at a faster speed from the hot top wall to the cold bottom wall, significantly increasing heat transfer. Figure 19 shows that the temperature gradient increases with the increase of Reynolds number. As the Re number shifts to 100 and 300, the theta value is higher indicated by the higher red region.

Figure 20 shows the streamlines for Re = 50, 100 & 300. Both clockwise and anticlockwise vortex is seen for Re = 50. For Re = 50, the center vortex is recirculating clock wisely while the vortexes in the corner side are recirculating anticlockwise. Similar types pattern also seen for Re = 100 & 300. The density of the vortex increases for Re = 300. The streamlines become steeper on the right and left side walls when Re = 300.

Figure 21 shows the Nusselt number increases almost linearly for Ri = 1. But at Ri = 10, the increase of Nu is not very significant. However, at Ri = 0.1, the observed Nu number is higher compared to others. So, forced convection can be a major parameter for increasing the heat transfer rate, and for future cavity design, as low as the Ri number, the higher would be the heat transfer.

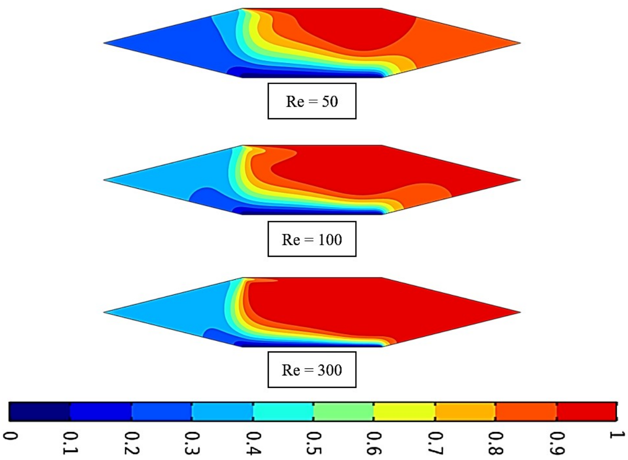


Fig. 19. Isothermal Contour for different values of Reynolds Number with Ha = 30, Ri = 0.1, Pr = 7 and magnetic inclination angle γ = 60°.

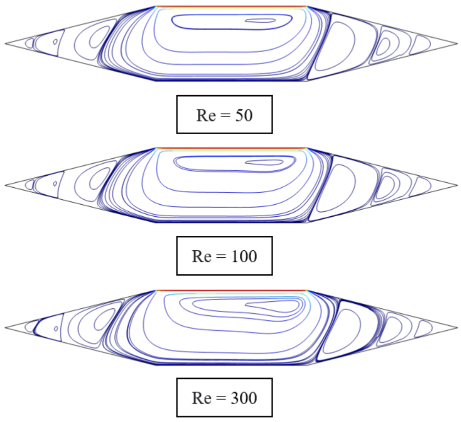


Fig. 20. Streamlines for different values of Reynolds Number with Ha = 30, Ri = 0.1, Pr = 7 and magnetic inclination angle γ = 60°.

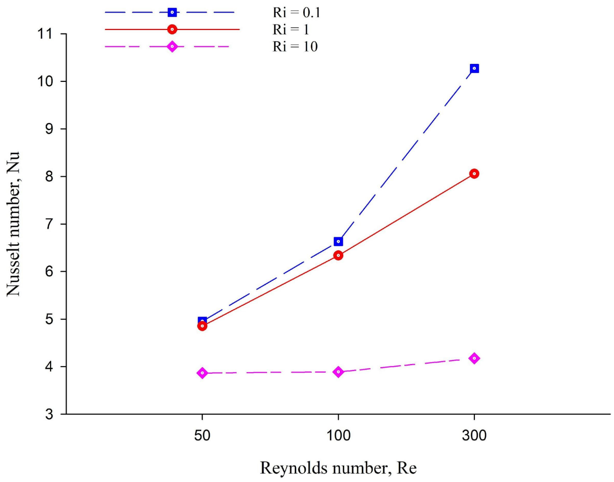


Fig. 21. Nusselt number along the top wall for different value of with Ri = 0.1,1,10, Ha = 30, Pr = 7, magnetic inclination angle γ = 60°.

5. Conclusion

A numerical analysis was performed in this study to observe the effect of convective transfer in a lid-driven enclosure. The important findings can be noted as:

I. Hexagonal-shaped cavity has the highest Nu number compared to the square, rhombus, rounded rectangle, trapezoid-shaped cavity.

II. Nu number increases with the increase of the Prandtl number.

III. The aspect ratio of the cavity is one of the important parameters in cavity design. Maximum heat transfer can be obtained with a higher aspect ratio defined in this study. In the present study, the Nu number decreases for increasing magnetic inclination angle when the aspect ratio is 2. But Nu number increases with the increase of magnetic inclination angle when the aspect ratio is 1.25. Hence, cavity shape and dimension are very important parameters in cavity design.

IV. Nu number increases for the lower value of Richardson number because forced convection is dominant over free convection at a lower Richardson number.

V. The Nu number decreases with the increase of the magnetic field inside the cavity. The magnetic field has a very less significant effect at a higher value of Richardson number because free convection is dominant over conduction effects of the fluid.

VI. As the forced convection is dominant while the increase of Reynolds number increases the Nu number.

Disclosures

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References

Ahmad Dar, A., & Elangovan, K. (2016). Influence of an Inclined Magnetic Field and Rotation on the Peristaltic Flow of a Micropolar Fluid in an Inclined Channel. New Journal of Science, 2016, 5717542. doi:10.1155/2016/5717542

Al-Amiri, A. M., Khanafer, K. M., & Pop, I. (2007). Numerical simulation of combined thermal and mass transport in a square lid-driven cavity. International Journal of Thermal Sciences, 46(7), 662-671.

Alleborn, N., Raszillier, H., & Durst, F. (1999). Lid-driven cavity with heat and mass transport. International Journal of Heat and Mass Transfer, 42(5), 833-853.

Bakar, N., Roslan, R., Karimipour, A., & Hashim, I. (2019). Mixed convection in lid-driven cavity with inclined magnetic field. Sains Malaysiana, 48(2), 451-471.

Bejan, A. (2013). Convection heat transfer: John wiley & sons.

Billah, M., Rahman, M., Sharif, U. M., Rahim, N., Saidur, R., & Hasanuzzaman, M. (2011). Numerical analysis of fluid flow due to mixed convection in a lid-driven cavity having a heated circular hollow cylinder. International Communications in Heat and Mass Transfer, 38(8), 1093-1103.

Dawood, M. M. K., & Teamah, M. A. (2012). Hydro-magnetic mixed convection double diffusive in a lid driven square cavity. European Journal of Scientific Research, 85(3), 336-355.

Khanafer, K. M., Al-Amiri, A. M., & Pop, I. (2007). Numerical simulation of unsteady mixed convection in a driven cavity using an externally excited sliding lid. European Journal of Mechanics-B/Fluids, 26(5), 669-687.

Krakov, M., & Nikiforov, I. (2002). To the influence of uniform magnetic field on thermomagnetic convection in square cavity. Journal of Magnetism and Magnetic Materials, 252, 209-211.

Moallemi, M., & Jang, K. (1992). Prandtl number effects on laminar mixed convection heat transfer in a lid-driven cavity. International Journal of Heat and Mass Transfer, 35(8), 1881-1892.

Munshi, M. J. H., Mostafa, G., Munsi, A. M., & Waliullah, M. (2018). Hydrodynamic Mixed Convection in a Lid-Driven Hexagonal Cavity with Corner Heater. American Journal of Computational Mathematics, 8(03), 245-258.

Nasrin, R., & Parvin, S. (2011). Hydromagnetic effect on mixed convection in a lid-driven cavity with sinusoidal corrugated bottom surface. International Communications in Heat and Mass Transfer, 38(6), 781-789.

Oztop, H. F., Al-Salem, K., & Pop, I. (2011). MHD mixed convection in a lid-driven cavity with corner heater. International Journal of Heat and Mass Transfer, 54(15-16), 3494-3504.

Rahman, M. M., Mamun, M. A. H., & Saidur, R. (2011). Analysis of magnetohydrodynamic mixed convection and joule heating in lid-driven cavity having a square block. Journal of the Chinese Institute of Engineers, 34(5), 585-599.

Rudraiah, N., Barron, R., Venkatachalappa, M., & Subbaraya, C. (1995). Effect of a magnetic field on free convection in a rectangular enclosure. International Journal of Engineering Science, 33(8), 1075-1084.

Saeid, N. H., & Yaacob, Y. (2006). Natural convection in a square cavity with spatial side-wall temperature variation. Numerical Heat Transfer, Part A: Applications, 49(7), 683-697.

Sivasankaran, S., Malleswaran, A., Lee, J., & Sundar, P. (2011). Hydro-magnetic combined convection in a lid-driven cavity with sinusoidal boundary conditions on both sidewalls. International Journal of Heat and Mass Transfer, 54(1-3), 512-525.

Sud, V., Sekhon, G., & Mishra, R. (1977). Pumping action on blood by a magnetic field. Bulletin of mathematical biology, 39(3), 385-390.

Tuckerman, D., & Pease, R. (1981). IIIB-8 implications of high performance heat sinking for electron devices. IEEE Transactions on Electron Devices, 28(10), 1230-1231.

Vafai, K., & Hadim, H. (2018). Overview of current computational studies of heat transfer in porous media and their applications-natural and mixed convection. Advances in Numerical Heat Transfer, 2, 331-369.