CFD assessment of MHD induced half sinusoidal bottom heated thermo-gravitational convective transport of hybrid nanofluid in porous cavity

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***Abstract* - A narrative loom in possessions of externally induced thermomagnetic field, nonuniform heating profile frequency, amplitude on fluid flow and heat transport of Cu-Al2O3 blended nanoparticles mixed with water called hybrid nanofluid within porous cavity is lucidly investigated in the present work. The problem geometry is half sinusoidal heated profile at bottommost wall anchored in a range of frequencies (f), amplitude (I) and cooled at the side walls. Fluids enter through two ports of bottom section of side walls and going out mid-center port of top wall. Finite Volume Method (FVM) is adopted for sprouting lab based numerical simulation and same is implemented for solution of governing complex equations. The exploration is conceded underneath the result of an option of important parameters as Re, Ri, Ha, Da, ε, ϕ. Heat lines, streamlines, Isotherms contours and linked heat transport rate of these parametric induced cases are examined scrupulously. This is examined that the energy transmit rate is augmented at elevated Re, Ri, Da and ϕ with the rising frequency whereas Ha values reduce average Nusselt values.**

***Keywords*: — Non-uniform heating; half sinusoidal frequency; hybrid nanofluid; magnetohydrodynamic (MHD); Heat lines.**

I. INTRODUCTION

Over the decade, ‘Nano’ a small word with immense potentiality has been promptly devious itself into the world’s realization. Nano science has stimulated from humankind of future to civilization of present. Technology adopted Nano material has been battering its existence reflect on industry, and numerous applications are already standardized. Erstwhile nanomaterials acquire unique, useful chemical, physical, and mechanical property; they might be utilized for an extensive assortment of applications be fond of next-gen computer technology, aeronautical mechanism, spaceship applications, and several others. Ultimately growth of nano technology products is owing to next industrial insurgency. Accepting major challenges in potential engineering apparatus and devices in recent times, this study explores the fundamental physics of mixed convection heat transport beneath external induced MHD field throughout a intricate porous configuration in a half sinusoidal heated enclosed area. The varied applications of allied issues replicated for example electronic device, heat exchangers, solar thermal appliance, and food processing engineering, MEMs and large numbers of others. Consequently, thermal supervision in convection contained by flow diminishing porous media and field of MHD amid heated source to cold sink has been a important topic of apprehension [1–3]. This sort of effect with heater and cooler base added intricate magneto-thermos-flow concern with additional multi-physical status. In this point of view, benefit of heating non-uniformly in porous enclosure is stated by Biswas et al. [4]. Afterward, Manna et al. [5] investigated that sinusoidal heating be able to an effectual way for enhancing heat transport rate in a thermos-flow system. Further comprehensive assessments on thermos-convective study with hybrid nanofluid or nanofluid are convincingly reported in references. [3, 5–7]. Bouncy-dominated convective flow in porous cavity containing special fluid adopting varying boundary provisions are highlighted by Ramakrishna et al. [7]. In the recent investigation, useful characteristic of Cu-Al_2O_3 blended pure water hybrid nanofluid non-uniform heating consequence under the control of heating with sinusoidal profile has been exhaustively scrutinized by Mondal et al. [14] and Tayebi and Chamkha [8].

Through this massive collection of accessible literatures, this is apprehended that half sinusoidal non-uniform heating relevance is applicable in a diversity of thermos-fluid structure for investigating heat transport added to suitable control to this system [9, 10]. Accordingly, intend of this examination is to learn magneto-thermo mixed convection with Cu-Al_2O_3-water packed porous enclosure with bottom wall heated half sinusoidally revealed in Fig. 1. Heating contour is employed at wall of enclosed space adopting nondimensional parameter as "amplitude (A)". Fluids enter through two ports of bottom section of side walls and going out mid-center port of top wall. The hot fluid is liberating heat throughout cold side walls along with fluid flown in cavity. Consequently, the present study is formulated and inspired by need to analyze thermos-flow and transport process of a half sinusoidal bottom heated area beneath a range of significant parameters like Reynolds, Hartmann, Darcy number and Cu-Al_2O_3 blended hybrid nano scale particles concentrations in water. The outcomes are presented by contour maps of streamlines, isotherms, heatlines and Nusselt average. Heatlines is the visualization tools to demonstrate the heat flux flow process from heat source to sink. In present work, the incorporation of flow in and out along with supplementary multi-physical events is a new role in this research area.

II. PHYSICAL DOMAIN AND FORMULATION

A schematic diagram of the problem geometry including the boundary settings is described in Fig. 1. The computational domain is two-dimensional (in x-y plane) square enclosure with length L and height H ($L = H$) composed of superposed hybrid nanofluid-porous substance. The enclosure is heated half sinusoidally (temperature T_h) at bottom wall is permitted to exchange heat with side walls (temperature T_c, such that $T_h > T_c$). Top wall are thermally insulated. Two bottom portions (of $w_i = 0.1L$) of both side walls are opened through which hybrid nanofluid, Cu−Al_2O_3-water enter and mid portion (of $w_o = 0.2L$) top wall is opened by which hot fluid going out. Enclosure is also composed of, saturated porous substances. External generated a uniform magnetic field of strength B may be induced (horizontally from left side wall) over entire length of enclosure.

The governing hyperbolic nonlinear equations are obtained for a 2-D flow of continuity, X and Y-momentum

$$\frac{1}{\varepsilon^2}\left(U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}\right)=-\frac{\rho_f}{\rho}\frac{\partial P}{\partial Y}+\frac{\nu}{\nu_f}\frac{1}{\varepsilon \mathrm{Re}}\left(\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}\right) \tag{3}$$

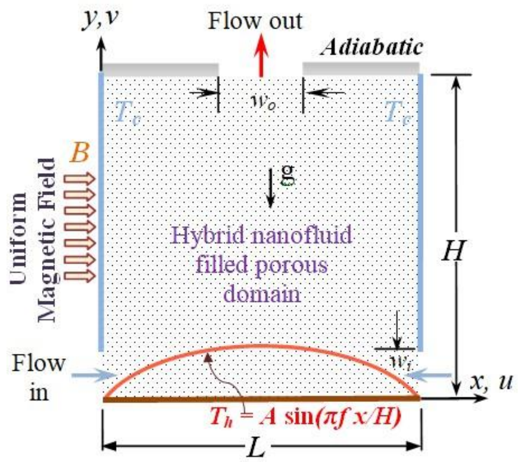
$$-\left(\frac{\nu}{\nu_f}\frac{1}{\mathrm{DaRe}}+\frac{F_c\sqrt{U^2+V^2}}{\sqrt{\mathrm{Da}}\,\varepsilon^{3/2}}\right)V+\frac{\rho_f}{\rho}\frac{\sigma}{\sigma_f}\frac{\mathrm{Ha}^2}{\mathrm{Re}}V+\frac{(\rho\beta)}{\rho\beta_f}\mathrm{Ri}\theta$$

$$\left(U\frac{\partial \theta}{\partial X}+V\frac{\partial \theta}{\partial Y}\right)=\frac{\alpha}{\alpha_f}\frac{1}{\mathrm{Re\,Pr}}\left(\frac{\partial^2 \theta}{\partial X^2}+\frac{\partial^2 \theta}{\partial Y^2}\right) \tag{4}$$

where,

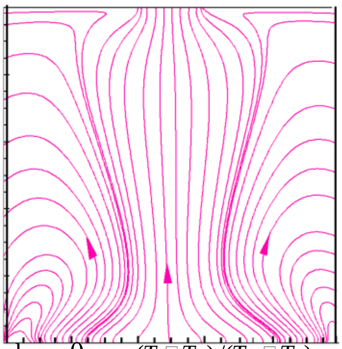
$$\mathrm{Re}=\frac{V_w H}{\nu_f};\ \mathrm{Pr}=\frac{\nu_f}{\alpha_f};\ \mathrm{Da}=\frac{K}{H^2};\ F_c=\frac{1.75}{\sqrt{150\,\varepsilon^{3}}}; \tag{5}$$

$$\mathrm{Ha}=B_o H\sqrt{\sigma_f/\mu_f};\ \mathrm{Ri}=\frac{\mathrm{Gr}}{\mathrm{Re}^2};\ \mathrm{Gr}=\frac{g\beta_f(T_h-T_c)H^3}{\nu_f^2};$$



and energy which are non-dimensional with length scale by L, velocity scale by V_w, also temperature and pressure

(a) Problem geometry and boundary



expressed by $\theta = (T - T_c)/(T_h - T_c)$ $P = (p - p_a)/\rho V_w^2$ respectively. Consequential dimensionless equations are

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \qquad (1)$$

$$\frac{1}{\varepsilon^2}\left(U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}\right)=-\frac{\rho_f}{\rho}\frac{\partial P}{\partial X}+\frac{\nu}{\nu_f}\frac{1}{\varepsilon \mathrm{Re}}\left(\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 U}{\partial Y^2}\right) \qquad (2)$$
$$-\left(\frac{\nu}{\nu_f}\frac{1}{\mathrm{Da}\,\mathrm{Re}}+\frac{F_c\sqrt{U^2+V^2}}{\sqrt{\mathrm{Da}}\,\varepsilon^{3/2}}\right)U$$

(b) Heatlines

Fig. 1. Schematic problem geometry of (a) physical domain (b) heat flow visualization.

In equations (1) – (4), non-dimension parameters are assigned by Reynolds number Re, Richardson number Ri, Grash of number Gr, Prandtl number Pr (= 5.83, constant), Darcy number Da, For chheimer coefficient F_c, and Hartmann number Ha. Also non-dimensional velocity components are U in X and V in Y coordinates and g is acceleration due to gravity. Likewise, subscript 'f' and 's' are employed to specify the thermos-physical properties for host fluid and solid nano scale particles respectively. The symbol 'ϕ' is used to symbolize the blend of hybrid-nanoparticles volumetric fraction. Effectual properties of hybrid nanofluid could be defined as

Mass density:

$$\rho = (1-\phi)\rho_f + \phi_{Al_2O_3}\rho_{Al_2O_3} + \phi_{Cu}\rho_{Cu} \qquad (6)$$

sp. heat capacity:

$$(\rho c_p) = (1-\phi)(\rho c_p)_f + \phi_{Al_2O_3}(\rho c_p)_{Al_2O_3} + \phi_{Cu}(\rho c_p)_{Cu} \quad (7)$$

Thermal expansion:

$$(\rho\beta) = (1-\phi)(\rho\beta)_f + \phi_{Al_2O_3}(\rho\beta)_{Al_2O_3} + \phi_{Cu}(\rho\beta)_{Cu} \quad (8)$$

Thermal conductivity:

$$k = k_f \left[\frac{(k_s + 2k_f) - 2\phi(k_f - k_s)}{(k_s + 2k_f) + \phi(k_f - k_s)} \right] \quad (9a)$$

$$\phi k_s = \phi_{Cu} k_{Cu} + \phi_{Al_2O_3} k_{Al_2O_3} \quad (9b)$$

Electrical conductivity:

$$\sigma = \sigma_f \left[1 + \frac{3(\sigma_s/\sigma_f - 1)\phi}{(\sigma_s/\sigma_f + 2) - (\sigma_s/\sigma_f - 1)\phi} \right] \quad (10a)$$

$$\phi\sigma_s = \phi_{Cu}\sigma_{Cu} + \phi_{Al_2O_3}\sigma_{Al_2O_3} \quad (10b)$$

Thermal diffusivity:

$$\alpha = \frac{k}{(\rho c_p)} \quad (11)$$

Viscosity:

$$\mu = \frac{\mu_f}{(1-\phi)^{2.5}} \quad (12)$$

The imposed boundary conditions for the current numerical simulation are as follows:

$U = V = \partial\theta/\partial Y = 0$ - top adiabatic wall

$U = V = 0,\ \theta = 0$ - left and right-side walls,

$\theta = A\sin(\pi f\ x/L)$, $V = U = 0$ for heated bottom wall

Flow in, $U = \pm 1$ (in either side), and flow out, $V = 1$

The average distribution of heat transport uniqueness over the active walls of the enclosure are calculated by the average Nusselt number (Nu) as formulated by

$$\mathrm{Nu} = \frac{k}{k_f}\int_0^1 \left(-\left.\frac{\partial\theta}{\partial Y}\right|_{X=0}\right) dX \quad (13)$$

Localized contour fluid-flow patterns within computational domain envisaged employing streamlines, which is considered from determined velocity fields by producing stream function ψ and is articulated as

$$-\frac{\partial\psi}{\partial X} = V \text{ and } \frac{\partial\psi}{\partial Y} = U \quad (14)$$

Additionally, transportations of heat flow are foreseen by by means of heat lines contour. The perception of heat lines is used here to signify the pathway of heat flux flow. The heat lines are principally produced from energy equilibrium in steady-state state and it is determined from heat function (Π), which may be formulated as

$$-\frac{\partial\Pi}{\partial X} = V\theta - \frac{\partial\theta}{\partial Y} \text{ and } \frac{\partial\Pi}{\partial Y} = U\theta - \frac{\partial\theta}{\partial X} \quad (15)$$

procedure, in anticipation of normalized maximum values of residuals and continuity mass defect go with less than 10^{-8} and 10^{-10}, respectively.

IV. RESULTS AND DISCUSSION

In current investigation, effect of half sinusoidal heating of bottom most walls with varying frequency on heat transfer and both way flow of blended hybrid nanofluid inside porous cavity under MHD effect is investigated in mixed convection. Consequences of varied related parameters are analyzed broadly for a choice of parametric variation as: Richardson number ($0.1 \le \mathrm{Ri} \le 100$), Reynolds number ($10 \le \mathrm{Re} \le 200$), Darcy value ($10^{-5} \le \mathrm{Da} \le 10^{-1}$), Hartmann number (0 (no field)$\le \mathrm{Ha} \le 70$), volume fraction (0 (no particle)$\le \phi \le 2\%$), treating porosity value $\varepsilon = 0.6$ and amplitude (A =1.0) fixed, and frequency magnitude chosen as f = 1 to 7. Results are demonstrated by means of flow path using streamlines, temperature distribution by isotherms, energy flux by visualization of heat lines contour and also heat exchanges in the system by Nusselt values.

A. *Impact of half sinusoidal heating frequency f*

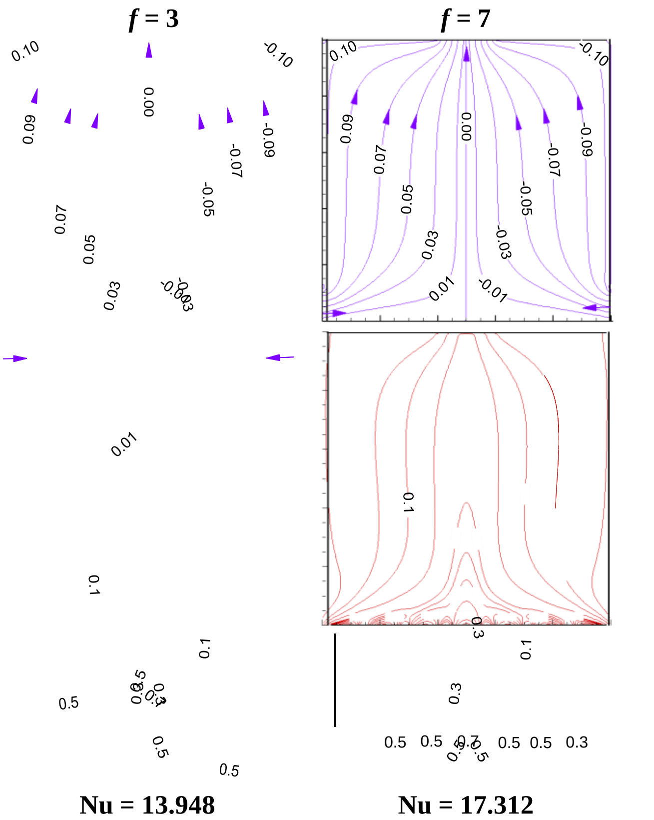


Fig. 2. Impact of *half sinusoidal heating multi frequency on* streamlines (first row), and isotherms (second row) at Re = 100, Ri = 10, Da = 10^{-3}, Ha

III. NUMERICAL METHODOLOGY

The governing equations (1) – (4) in conjunction with suitable boundaries identify a set of nonlinear, non-dimensional coupled differential equations are solved in succession by means of indigenous CFD program implementing FVM approach. The set of equations are initially converted into algebraic forms, which are being iteratively solved through TDMA solver and ADI sweep using SIMPLE algorithm. Non-uniform staggered grid (160×160) distributions are used for the discretization. Converging solutions are acquired throughout the iteration

= 30, ϕ = 0.1%.

Impact of multi frequency of non-uniform half-sinusoidal heating thermal profile on thermos-flow is looked into and exemplified in Fig. 2 for two frequency f = 3, and 7 maintaining other parameters constant as defined. Temperature distribution, demonstrates alike dynamics excepting for bottom section (close to hot wall) of cavity and perseveres for any frequencies as also shown in Fig. 3. Of course, near source wall thermos- flow performance happen to more susceptible and complicated at elevated frequencies. Augment in frequency, flow configurations do not change distinctly, excepting lower section close to source bottom wall. With rise in frequency value, a number of tiny thermal energy recirculation cells appear, and this number is essentially a function of heating frequency. Temperature allocation (isotherms) closer to source wall specify the existence of unlike peaks numbers as 3 peaks for f = 3, 7 peaks for f = 7 for heating frequency). Obviously, fluid temperature layers, near to hot wall modifies following state of heating. Flow pattern in both frequencies show similar as reflected by streamlines

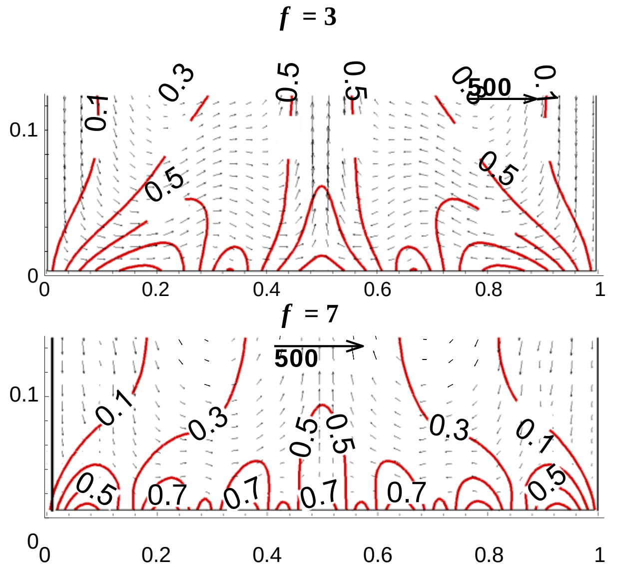


Fig. 3. *Multi frequency impact on* vector and isotherms contour near to hot boundary at Re=100, Ri = 10, Da = 10^{-3}, Ha = 30, ϕ = 0.1%.

B. *Impact of flow velocity (Re)*

The influence of flow velocity defined by Reynolds number Re on the thermo-hydrodynamics is investigated utilizing different velocities of hybrid nanofluid through active ports of side walls viewed in Fig. 4. Using same fluid and flow domain, unlike velocities are enforced through Re = 10 and 200. Upward velocity of fluid through mid-port of top wall, $v_w = 1$ are considered. Other conditions are taken at Ri = 1, Ha = 30, Da = 10^{-3} and ϕ = 0.1%. At the lower value of Re = 10, the flow structure is dominated by the forced convection. Equivalent heat transfer is governed by thermal conduction. This is obvious from distortion-free isotherms which are disseminated in straightway following profile of active parts of heat source. Energy transportation through heat lines takes place straight forward inflow to outflow allied to hot bottom wall to cold side walls.

However, with augmented Re = 200, the buoyancy dominated flow turn into stronger. The existence of traditional flow-scenarios appears in the enclosure. While Re rises, Gr raises by square of Re. With constant Ri, as Re have an effect on both fluid motion and Gr, elevated Re value severely impacts on flow structures of contour. Energy recirculation in heat lines contours is distributed symmetrically about upright mid-plane which covers entire cavity. Thus, heat flows (from heater to cooler) during long fluid flow paths. Heat lines structure for both low and high

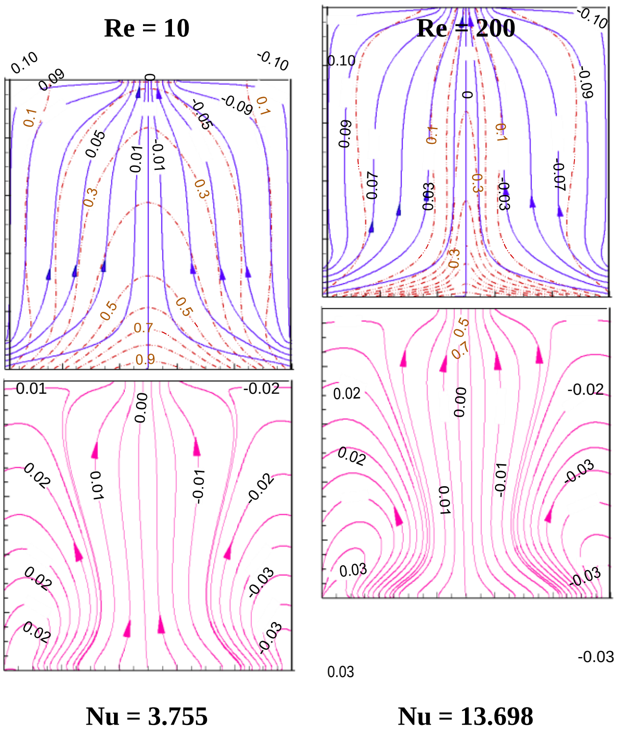
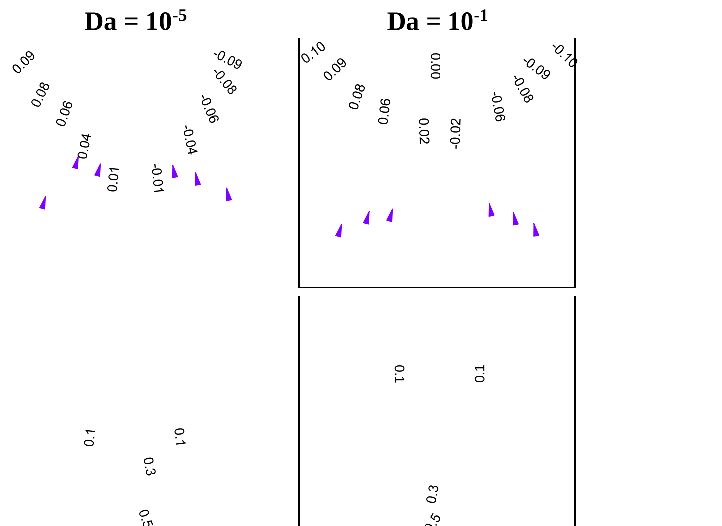


Fig. 4. Reynolds number (Re) impact on streamlines-isotherms coupling (first row), and heat lines (second row) at Ri = 1, Da = 10^{-3}, Ha = 30, ϕ = 0.1%, f = 1.

C. *Outcome of Darcy number* (Da) *on porous media*



Re seems nicely flower vase pattern. The magnitudes of Nu specify heat transmit is radically augmented at higher Re.

Nu = 7.357 **Nu = 12.529**

Fig. 5. Porous matrix permeability impact by Darcy number (Da) on streamlines and isotherms at Re=100, Ri = 10, Ha = 30, ϕ = 0.1%, *f* = 1.

Outcome of Darcy number, Da with unchanging Re = 100, Ri = 10, ϕ = 0.1%, Ha = 30, and *f* = 1 are represented in

Fig. 5 for low to high Da (10^{-5} to 10^{-1}). Normally, less Da is correlated to high resistive porous matrix. Both fluid flows and energy flux progress with high resistance accordingly lessen Nu average value. In augmented Da = 10^{-1}, as knowable with better permeability lesser might be flow resistance. Symmetrical flows come out in plots of streamlines contour and also some distorted contour near inflow path of flow. Subsequent isotherms are symmetrical but curvilinearly disseminated from source to sinks.

Therefore, fluid-based Da indicates a high thermal convection at Da = 10^{-1} comparison to Da = 10^{-5}. Accordingly, overall transmission of heat enhances substantially as reproduced by Nu average values. In addition, choice of Da value manages the thermos-flow heat and cool system along with pathway of nanofluid flow.

D. Intensity of uniform magnetic field (Ha)

MHD impact attributable to horizontal magnetizing field (relating to Ha number) on contours pattern of streamlines and isotherms are visualized in Fig. 6 for varying of Ha = 0(no field), 70 maintain supplementary parameters invariable at Re=100, Ri = 1, Da = 10^{-3}, ϕ = 0.1%, f = 1.

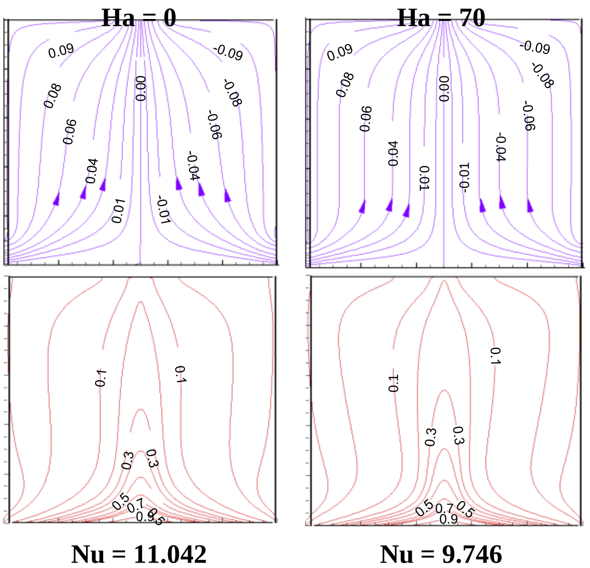


Fig. 6. Magnetic field potency based on Hartmann number (Ha) on contour of streamlines (first row), and isotherms (second row) at Re=100, Ri = 1, Da = 10^{-3}, ϕ = 0.1%, f = 1.

For better investigation, case of absent of magnetic field, Ha = 0 is examined first as epitomized in Fig. 6 followed by high Ha = 70. The flow pattern reflects a symmetric distribution comparative to upright mid-plane. With escalation imposed magnetizing field by increasing Ha value = 70, pattern wise in general flow arrangement are similar with pattern at no field. However, buoyancy-domination becomes weaker which leads to smaller heat transportation and reduction is extreme at elevated Ha = 70.

From the momentum equations as in Eqn. (3), it is perceptible that existence of negative terms with Ha reduces in vertical velocity part as Ha increases. Consequently, magnetizing force counters the positive value of buoyancy force. It governs in further diminution in flow velocity, impacting energy Eq. (4); resulting reduction in energy exchange with rising Ha values. Allied heat transmit rate also reduces as replicated by Nu values.

E. Hybrid Nanoparticles volume fraction (ϕ) influence

The raise in volumetric concentration ϕ = 0.33% and 2% of blended Cu-Al_2O_3 nano-powders and pure water as working fluid on streamlines, isotherms contour and Nu

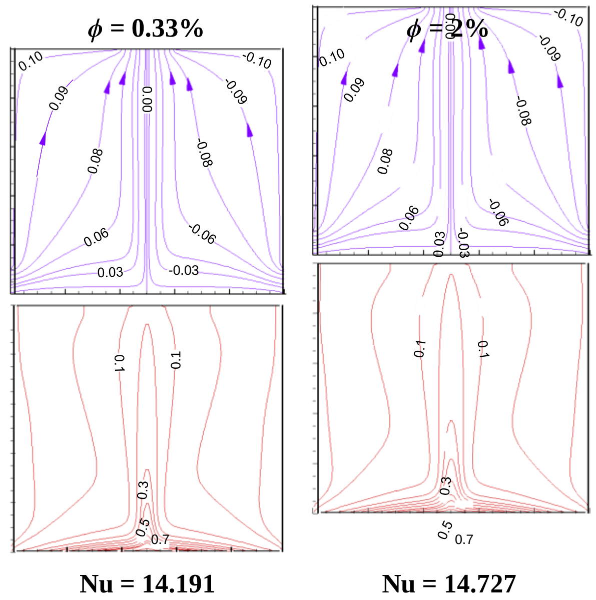


Fig. 7. Inclusion of hybrid nanoparticle volume fraction (ϕ) on streamlines (top panel), and isotherms (bottom panel) at Re=100, Ri = 100, Da = 10^{-3}, Ha = 30, f = 1.

This is reasonably obvious that, inclusion of nanoscale blended hybrid powder in host liquid water owing to augment in flow circulation potency, thereby slight enhancement in heat transport rate. The prime reason behind this augmentation is owing to raise in ϕ governs to increase in effective thermal conductivity of working media as hybrid nanofluid in such mixed convective system.

F. Heat transfer characteristics

average value are confirmed in Fig. 7 for same values of Re=100, Ri = 100, Da = 10^{-3}, Ha = 30, f = 1.

Heat transport features shown by Nu curve of the half sinusoidal heated with external flow in and out cavity are plotted in special parametric deviations of Ha, Da, Re, and ϕ for varying Ri within 0.1 to 100 with flow velocity in Fig.
8(a – d). The preset parameters are fixed as f = 1, A = 1, and ε = 0.6. Heat transfer curves are appraised based average Nusselt Nu as formulated in Eq. (13).

Figure 8a reflects Reynolds number variation for an assortment of Re = 10 to 200. With Ri ≤ 1, there is almost analogous consequence of Nu on Re. Though, with Ri = 10 and above, Nu significantly enhances with Re. At elevated Re > 50, heat transmission rate is more. The basis of such augmentation is owing to the truth that as Re raise (with other parameters constant), subsequent Grash of number raises, resulting considerable enhance in buoyancy impact.

Figure 8b reflects Nu curves a continually enhancing trend amid other parameter fixed with increasing of Da value. Rising trend is about analogous for each Ri values. The justification of this verity may be obscured by visualizing the flow configuration at higher Da (as viewed in Fig. 5). As Da increases, resistance to flow through porous media lessens, owing to increase heat transmission.

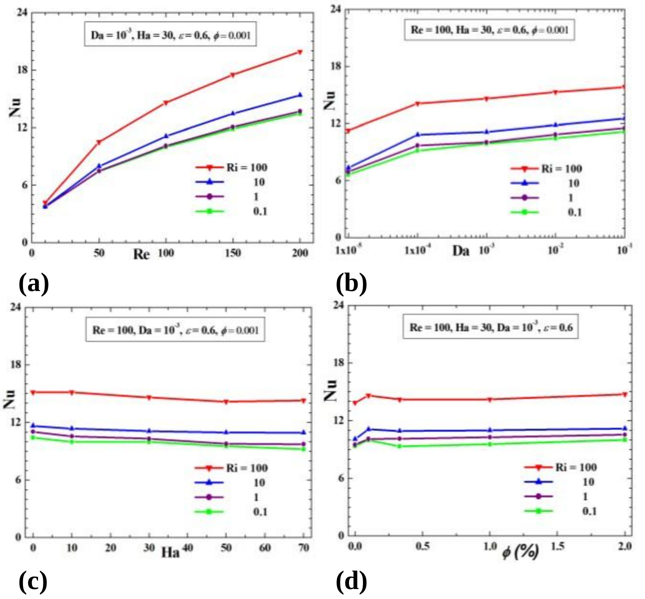


Fig. 8. Heat transport features with altering (a) Reynolds number, (b) Darcy number, (c) Hartmann number and (d) nanoparticle volume fraction

Figure 8c shows consistent declining Nu values with intensifying the magnetizing field, as Ha. This come about buoyancy impact resists the existence of imposed field. Declining trend of Nu plots is almost identical for all 'Ri' value. Buoyant force is counteracted by Magnetizing force that may be actually recognized by observing fluid stream and heat flux flow configuration at higher Ha (as reflected in Fig. 6). Therefore heat transportation progression is affected scrupulously.

Effect of volume fraction alteration of Cu-Al_2O_3 blended nanosize particles for changeable 'Ri' values is shown in Fig. 8d with unvarying parameters. Figure clearly replicates that, with increase in ϕ average Nu increases for 'Ri' values as Nu values for ϕ = 0.33% – 2% shows increasing trend relative to ϕ = 0. This is obvious that at ϕ = 0.1% Nu value is peak which maximizes the option of volume concentration for entire investigation.

V. CONCLUSIONS

A novel investigation leading to active bottom wall with half sinusoidally heating and side walls cooling isothermally along with flow in and out, resulting on transport of heat energy and working fluid medium uniqueness throughout porous area filled with hybrid-nano scale particles blended in base fluid water amid imposed uniform horizontal magnetizing field is analyzed by mathematical simulation adopting FVM. The magneto-thermos-flow phenomena are scrutinized based on exclusive parametric variations like Re, Da, Ha and ϕ. The notable abridgments are accomplished as:

- In MHD based convective system, heat transport characteristic is enhanced significantly for elevated Re and Ri which replicated by the selection of Re, Ri value.
- Intensity of buoyancy supremacy and porous media permeability counteract resistance to flow with intensification in Darcy magnitude within cavity. This outcome for augmentation in heat transfer rate. Such enhancement rate is more prominent at advanced Da.

- Rise in magnetic field strength value, consequence of buoyancy power be in opposition to magnetizing strength following in diminution of heat transmission rate.
- Added blending of hybrid nano-sized particles with base fluid in range of ϕ = 0.33% – 2%, the heat transfer rate increases in respect of host fluid ($\boldsymbol{\phi}$ = 0) whereas that is maximum at 0.1%.

In finale, this investigation probably will be constructive for designing the exclusive mechanisms where the modest alteration in managing of transport event is a key apprehension. This comprehensive instruction on the present study in view of a blending of solid-fluids flow medium and multi-magneto-thermos-physical circumstances might be the potential opportunity extent of R & D work.

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