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## Magnetohydrodynamic Natural Convection of Ternary Hybrid Nanofluid in a Corrugated Porous Enclosure

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# Magnetohydrodynamic Natural Convection of Ternary Hybrid Nanofluid in a Corrugated Porous Enclosure: A Finite Element Study for Efficient Aerospace Thermal Management



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# Statement of the Problem



**Problem description:** The study investigates steady-state natural convection in a Newtonian ternary hybrid ($CuO - Al_2O_3 - Fe_3O_4 / H_2O$) nanofluid contained within a double-corrugated rectangular enclosure saturated with a porous medium, as illustrated in Fig. 1.

**Flow assumptions:** The fluid flow is assumed to be two-dimensional, steady, laminar, and incompressible.

**Geometry:** The height ($H = 0.5$) and length ($L = 1$). The upper and lower horizontal walls exhibit sinusoidal corrugations with amplitudes ($n$) and ($a$), respectively.

**Central obstacle:** A plus-shaped cylinder is positioned at the centre of the cavity. It consists of two identical rectangles of length ($l = 0.2$) and width ($w = 0.025$), intersecting perpendicularly at their midpoints. The corners are rounded with a fillet radius of ($R_f$=0.01).

**Thermal boundary conditions:** The upper corrugated wall is thermally insulated. The plus-shaped cylinder and the lower corrugated wall are maintained at a constant hot temperature ($T_h$) only at locations A and B. The remaining portion of the bottom wall and both vertical sidewalls are maintained at the cold temperature ($T_c$).

**Magnetic field:** A uniform magnetic field of magnitude ($B_o$) is applied at an inclination angle ($\gamma$) relative to the horizontal direction.

**Gravitational field:** Gravity acts vertically downward along the negative y-axis.

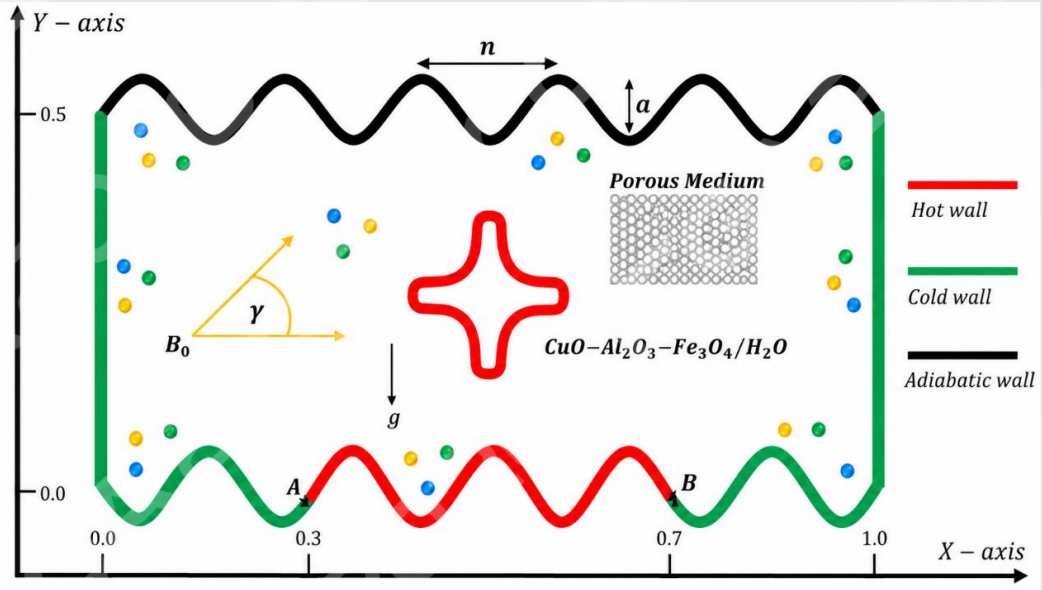
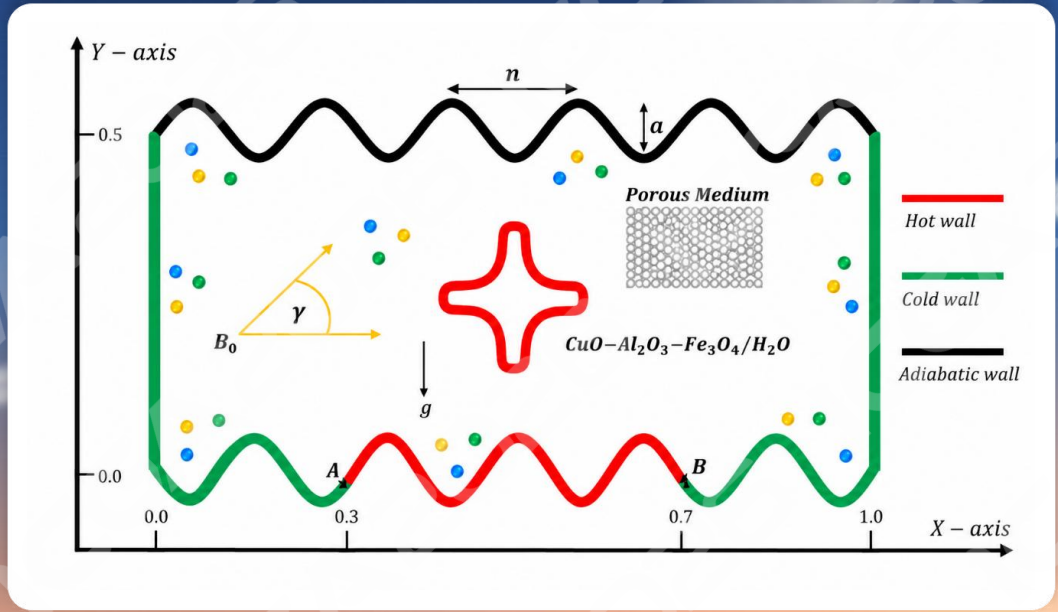



Fig. 1. Physical configuration of the problem

# Geometry Meets Green Aviation






*Our geometry: a wavy, porous cavity with a plus-shaped cylinder*

**Why it matters:** better cooling means lighter, smaller systems, less energy use and lower emissions.

1

## Avionics cooling

Wavy walls and porous layers help spread heat from compact electronic units.

2

## Battery thermal control

Electric and hybrid-electric aircraft need compact, efficient battery cooling.

3

## Compact heat exchangers

Wavy surfaces add heat-transfer area for engine and cabin systems.

4

## Magnetic nanofluid control

A magnetic field can steer the flow of a ternary hybrid nanofluid coolant.

# Applications of Geometry of the Current Problem



## 1. Solar Thermal Collectors



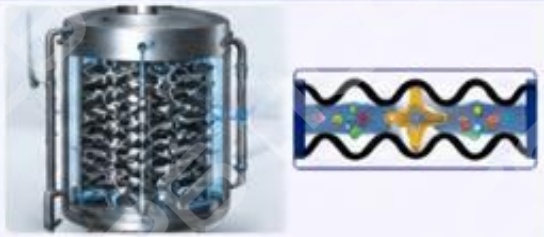
Wavy channels with obstacles enhance heat transfer in solar thermal collectors.

## 2. Electronic Device Cooling



Improves heat removal from high-power electronic components.

## 3. Chemical Reactors



Wavy geometries increase mixing and reaction rates in chemical reactors.

## 4. Heat Exchangers



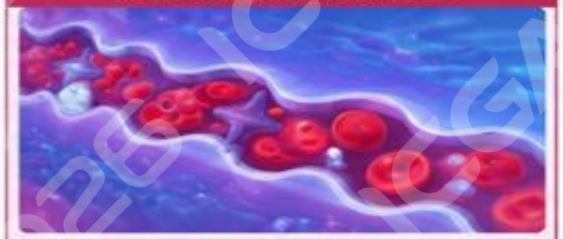
Corrugated channels provide high surface area and better heat transfer in compact heat exchangers.

## 5. Geothermal Energy Systems



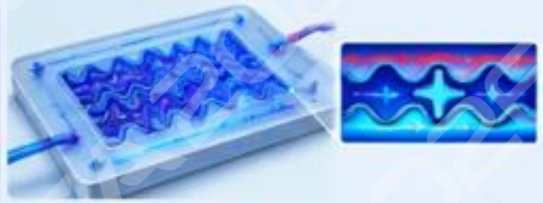
Wavy porous channels enhance heat extraction from geothermal reservoirs.

## 6. Biomedical Applications



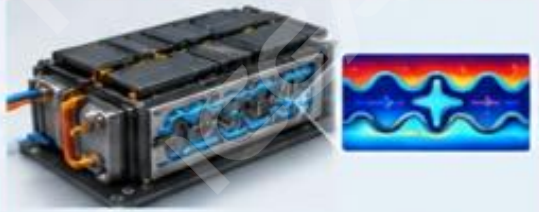
Used in drug delivery and biofluid analysis devices with enhanced mixing and mass transfer.

## 7. Microfluidic Devices



Wavy microchannels improve mixing and reaction efficiency in lab-on-chip systems.

## 8. Energy Storage (Battery Cooling)



Enhances thermal management in batteries and fuel cells.

## 9. Desalination Systems



Improves heat and mass transfer in membrane distillation and desalination units.

## 10. Aerospace & Automotive Cooling



Applied in turbine blades, heat sinks and advanced cooling systems.

# Basic Fundamental Laws



## Law of conservation of mass:

The rate of mass entering and exiting a system is remain same. Also stated that mass cannot be created and nor destroyed.

$$\nabla \cdot \boldsymbol{V} = 0 \tag{1}$$

## Law of conservation of momentum:

This law states that the total linear momentum of a system remains constant. It is based on Newton's second law, which states that the sum of forces acting on a fluid is equal to the product of the mass of the fluid and its acceleration.

$$\rho \frac{D\boldsymbol{V}}{Dt} = \nabla \boldsymbol{p} + \rho \vec{\boldsymbol{g}} + \mu \nabla^2 \boldsymbol{V} \tag{2}$$

Where, Total derivative $\rho \frac{D\boldsymbol{V}}{Dt} = \rho \left[\frac{\partial \boldsymbol{V}}{\partial t} + (\boldsymbol{V}.\nabla)\boldsymbol{V}\right]$, $\frac{\partial \boldsymbol{V}}{\partial t}$ =Change of velocity with time, and $[(\boldsymbol{V}.\nabla)\boldsymbol{V}]$ =Convective term, $\nabla \boldsymbol{p}$ =preassure gradient, $\rho \vec{\boldsymbol{g}}$ = Body Force term (gravitational force or electromagnetic), $\mu \nabla^2 \boldsymbol{V}$ = Diffusion term (Newtonian fluid, viscosity operates as a diffusion of momentum).

## Law of conservation of energy

It is derived from the first law of thermodynamics. It states that energy can be transformed from one form to another, and the total energy of the system is conserved.

$$\rho c_p \frac{D\boldsymbol{T}}{Dt} = k \nabla^2 \boldsymbol{T} + \hat{\Phi} \tag{3}$$

Where $\rho$=density, $c_p$= specific heat, $k$ = thermal conductivity, $\hat{\Phi}$= Viscous Dissipation.



**Analytical solutions are rare**

# Mathematical Model in Dimensional Form



After using the aforementioned assumptions, the fundamental Eqs. (4)-(7) become as follows: [1]

- **Continuity Equation**

$$U_X + V_Y = 0 \tag{4}$$

- **X- Component**

$$\frac{\rho_{TNF}}{\varepsilon^2}(UU_X + VU_Y) + P_X = \frac{\mu_{TNF}}{\varepsilon}(U_{XX} + U_{YY}) - \frac{\mu_{TNF}}{K}U - \frac{C_F\rho_{TNF}}{\sqrt{K}}(U^2 + V^2)^{\frac{1}{2}}U - F_{L,X} \tag{5}$$

- **Y- Component**

$$\frac{\rho_{TNF}}{\varepsilon^2}(UV_X + VV_Y) + P_Y = \frac{\mu_{TNF}}{\varepsilon}(V_{XX} + V_{YY}) - \frac{\mu_{TNF}}{K}V - \frac{C_F\rho_{TNF}}{\sqrt{K}}(U^2 + V^2)^{\frac{1}{2}}V + (\rho\beta)_{TNF}g(T - T_C) - F_{L,Y} \tag{6}$$

- **Energy Equation**

$$(\rho C_p)_{TNF}(UT_X + VT_Y) = k_{TNF}(T_{XX} + T_{YY}) \tag{7}$$

Where, $F_{L,X} = \sigma_{TNF}B_o^2(Usin^2\gamma - Vsin\gamma cos\gamma)$, $F_{L,Y} = \sigma_{TNF}B_o^2(Vcos^2\gamma - Usin\gamma cos\gamma)$, $\mu_{TNF}$, $K$, $\varepsilon$, $C_F$, $g$, and $T_C$, represents the effective density, the effective dynamic viscosity, the permeability of the porous medium, the porosity, the Forchheimer coefficient, the gravitational acceleration, and the cold wall temperature, respectively. The Darcy terms: $\frac{\mu_{TNF}}{K}U$ and $\frac{\mu_{TNF}}{K}V$, show the resistance exerted by the porous matrix, while the Brinkman terms: $\frac{\mu_{TNF}}{\varepsilon}\nabla^2 U$ and $\frac{\mu_{TNF}}{\varepsilon}\nabla^2 V$, account for viscous momentum diffusion inside the porous medium. The nonlinear Forchheimer expression denotes inertial resistance at higher flow velocity.

# Boundary Conditions (Dimensional form)



The applied boundary conditions follow the problem geometry in Fig. 2.

$$\frac{\partial T}{\partial Y}\left(X, Y = a\sin(n\pi X)\right) = 0, \text{ at } 0 \le X \le L, \tag{8}$$

$$T\left(X,\ Y = -\ a\sin(n\pi X)\right) = T_C, \text{ at } 0 \le X \le A, \tag{9}$$

$$T\left(X,\ Y = -\ a\sin(n\pi X)\right) = T_C, \text{ at } B \le X \le L, \tag{10}$$

$$T(X = 0,\ 0 \le\ Y \le 0.5L) = T_C, \text{ at } T(X = 1,\ \ 0.5L \le Y \le 0) = T_C, \tag{11}$$

$$T\left(X = L,\ Y = -\ a\sin(n\pi X)\right) = T_h,\ X = |AB|, \tag{12}$$

Star-shaped cylinder: $T(X = 0.5L,\ Y = 0.25L) = T_h$, (13)

At each wall of the geometry and cylinder: $U = V = 0$. (14)

Where $n,\ a,$ and $|AB|$ represents the wavelength, amplitude, and the length of the partially heated wall of the cavity.

# Effective Properties of the Ternary Nanofluid [2 - 3]



**Volume fraction**

$$\varphi = \varphi_1 + \varphi_2 + \varphi_3 \qquad \varphi_1 = CuO,\ \varphi_2 = Al_2O_3, \text{ and } \varphi_3 = Fe_3O_4 \tag{15}$$

**Density**

$$\rho_{TNF} = (1-\varphi)\rho_F + \varphi_1\rho_1 + \varphi_2\rho_2 + \varphi_3\rho_3 \tag{16}$$

**Heat capacity**

$$(\rho C_p)_{TNF} = (1-\varphi)(\rho C_p)_F + \varphi_1(\rho C_p)_1 + \varphi_2(\rho C_p)_2 + \varphi_3(\rho C_p)_3 \tag{17}$$

**Thermal Expansion**

$$(\rho\beta)_{TNF} = (1-\varphi)(\rho\beta)_F + \varphi_1(\rho\beta)_1 + \varphi_2(\rho\beta)_2 + \varphi_3(\rho\beta)_3 \tag{18}$$

**Dynamic Viscosity**

$$\mu_{TNF} = \frac{\mu_F}{(1-\varphi_1)^{2.5}(1-\varphi_2)^{2.5}(1-\varphi_3)^{2.5}} \tag{19}$$

**Thermal Conductivity**

$$\begin{cases} \text{first introduce } (CuO): & k_{NF} = k_F\left[\dfrac{k_1 + 2k_F + 2\varphi_1(k_1 - k_F)}{k_1 + 2k_F - \varphi_1(k_1 - k_F)}\right] \\ \text{then introduce} (Al_2O_3): & k_{HNF} = k_{NF}\left[\dfrac{k_2 + 2k_{NF} + 2\varphi_2(k_2 - k_{NF})}{k_2 + 2k_{NF} - \varphi_2(k_2 - k_{NF})}\right] \\ \text{finally } (Fe_3O_4) \text{is added:} & k_{TNF} = k_{HNF}\left[\dfrac{k_3 + 2k_{HNF} + 2\varphi_3(k_3 - k_{HNF})}{k_3 + 2k_{HNF} - \varphi_3(k_3 - k_{HNF})}\right] \end{cases} \tag{20}$$

**Electric Conductivity**

$$\begin{cases} \text{first introduce } (CuO): & \sigma_{NF} = \sigma_F\left[\dfrac{\sigma_1 + 2\sigma_F + 2\varphi_1(\sigma_1 - \sigma_F)}{\sigma_1 + 2\sigma_F - \varphi_1(\sigma_1 - \sigma_F)}\right] \\ \text{then introduce} (Al_2O_3): & \sigma_{HNF} = \sigma_{NF}\left[\dfrac{\sigma_2 + 2\sigma_{NF} + 2\varphi_2(\sigma_2 - \sigma_{NF})}{\sigma_2 + 2\sigma_{NF} - \varphi_2(\sigma_2 - \sigma_{NF})}\right] \\ \text{finally } (Fe_3O_4) \text{is added:} & \sigma_{TNF} = \sigma_{HNF}\left[\dfrac{\sigma_3 + 2\sigma_{HNF} + 2\varphi_3(\sigma_3 - \sigma_{HNF})}{\sigma_3 + 2\sigma_{HNF} - \varphi_3(\sigma_3 - \sigma_{HNF})}\right] \end{cases} \tag{21}$$

# Thermophysical Properties



| Parameter | Units | $H_2O$ | $CuO$ | $Al_2O_3$ | $Fe_3O_4$ |
|---|---|---|---|---|---|
| $\rho$ | $kg/m^3$ | 997.1 | 6320 | 765 | 5180 |
| $C_p$ | $J/kgK$ | 4179 | 531.8 | 3970 | 670 |
| $k$ | $W/mK$ | 0.613 | 76.5 | 40 | 9.7 |
| $\beta$ | $1/K$ | $2.1\times10^{-4}$ | $1.8\times10^{-5}$ | $0.85\times10^{-5}$ | $1.3\times10^{-5}$ |
| $\sigma$ | $(\Omega.m)^{-1}$ | 0.05 | 34.5 | $10^{-10}$ | $0.74\times10^{6}$ |

Table 1. Thermophysical properties of the base fluid and induced nanoparticles [2 - 3].

# Dimensionless Parameters

The introduced dimensionless variables are as follows:

$$x = X/L, \tag{22}$$

$$y = Y/L, \tag{23}$$

$$u = UL/\alpha_{TNF}, \tag{24}$$

$$v = VL/\alpha_{TNF}, \tag{25}$$

$$\theta = (T - T_C)/(T_h - T_C), \tag{26}$$

$$p = PL^2/(\rho_{TNF}\alpha_{TNF}^2). \tag{27}$$

# Mathematical Model in Non-dimensional Form



After substituting Eqs. (22 - 27) into Eqs. (4 - 7) becomes:

- **Continuity Equation**

$$u_x + v_y = 0 \tag{28}$$

- **X- Component**

$$\frac{1}{Pr\varepsilon^2}(uu_x + vu_y) + p_x = \frac{1}{\varepsilon}(u_{xx} + u_{yy}) - \frac{1}{Da}u - \frac{C_F}{\sqrt{Da}}(u^2 + v^2)^{\frac{1}{2}}u - Ha^2(usin^2\gamma - vsin\gamma cos\gamma) \tag{29}$$

- **Y- Component**

$$\frac{1}{Pr\varepsilon^2}(uv_x + vv_y) + p_y = \frac{1}{\varepsilon}(v_{xx} + v_{yy}) - \frac{1}{Da}v - \frac{C_F}{\sqrt{Da}}(u^2 + v^2)^{\frac{1}{2}}v + \frac{Ra}{Pr}\theta - Ha^2(vcos^2\gamma - usin\gamma cos\gamma) \tag{30}$$

- **Energy Equation**

$$u\theta_x + v\theta_y = \theta_{xx} + \theta_{yy} \tag{31}$$

# Involved Physical Parameters



Some physical quantities that are obtained while solving the given problem are given below:

**Grashof Number**

$$Ra = \frac{Buoyancy\ Forces}{.Viscous\ Forces \times thermal\ diffusion} = \frac{g\beta_{TNF}(T_h - T_C)L^3}{\alpha_{TNF}\,\vartheta_{TNF}},$$

**Prandtl Number**

$$Pr = \frac{Momentum\ Diffusivity}{Thermal\ Diffusivity} = \frac{\vartheta_{TNF}}{\alpha_{TNF}} = \frac{\mu_{TNF}(\rho C_p)_{TNF}}{\rho_{TNF} k_{TNF}},$$

**Hartmann Number**

$$Ha = \frac{Magnetic\ Forces}{Viscous\ Forces} = B_\circ L\sqrt{\frac{\sigma_{TNF}}{\mu_{TNF}}},$$

**Darcy Number**

$$Da = \frac{Permeability\ of\ a\ porous\ medium}{Characteristics\ Height} = \frac{K}{L^2}.$$

β = thermal expansion, g = gravitational acceleration, υ = Kinematic viscosity, α = thermal diffusivity, $B_\circ$= Magnetic flux density, L = Characteristic length, σ = Electrical conductivity, K = Permeablity.

# Boundary Conditions (Non-dimensional form)



After utilizing the dimensionless variables in Eqs. (8 – 14), the boundary constraints become:

$$\frac{\partial\theta}{\partial y}\left(x,\ \ y = asin(n\pi x)\right) = 0, \text{ at } 0 \le x \le 1, \tag{34}$$

$$\theta\left(x,\ \ y = -asin(n\pi x)\right) = 0, \text{ at } 0 \le x \le 0.3, \tag{35}$$

$$\theta\left(x,\ \ y = -asin(n\pi x)\right) = 0, \text{ at } 0.70 \le x \le 1, \tag{36}$$

$$\theta(x = 0,\ \ 0 \le y \le 0.5) = 0, \text{ at } \theta(x = 1,\ \ 0.5 \le y \le 0) = 0, \tag{37}$$

$$\theta\left(x = 1,\ \ y = -asin(n\pi x)\right) = 1,\ 0.30 \le x \le 0.70, \tag{38}$$

Star-shaped cylinder: $\theta(0.5,\ 0.25) = 1$, (39)

At each wall of the geometry and cylinder: $u = v = 0$. (40)

Where $n = 11,\ a = 0.05,$ and $|AB| = 0.4655$ are fixed.

# Quantities of Engineering Interest



## Nusselt Number

The Nusselt number is the ratio of convective to conductive heat transfer across a boundary.

$$Nu = \frac{q_{conv}}{q_{cond}} = \frac{hL}{k}$$

The local dimensionless heat transfer coefficient for the heated surface is defined as:

$$Nu = -\frac{\partial \theta}{\partial n}, \tag{41}$$

where $(n)$ is the outward normal direction.

The average Nusselt number $(Nu_{Avg})$ over the heated boundary $(\Gamma_h)$ is:

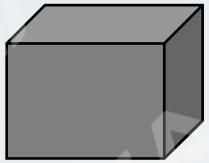
$$Nu_{Avg} = \frac{1}{L_h}\int_{\Gamma_h} -\frac{\partial \theta}{\partial n}\,ds. \tag{42}$$

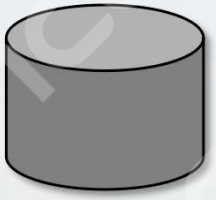
Where $(L_h)$ is the dimensionless length of the heated surface.

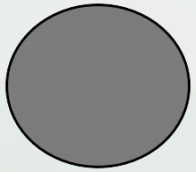
# Numerical Methodology



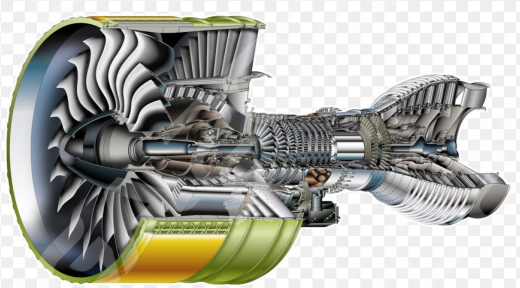








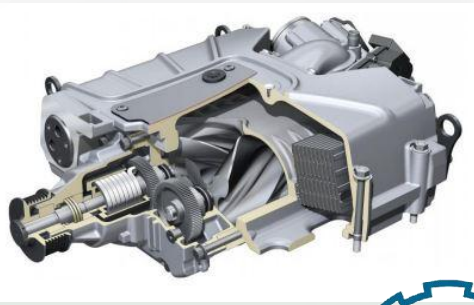
The solution of the governing equations (Navier-Stokes and Energy) is not easy to find analytically. For real-life cases, such as flow inside pumps, turbines, condensers, compressors, aircraft, and abodes, we have to turn to numerical methods to get insight.



Different computational methods are applicable to subdivide the entire domain into several elements or points or volumes that make the approximations close to that of the exact solution.

Based on discretization methodology, different types of solution methods are available, namely:

- Finite Volume Method (FVM)
- **Finite Element Method (FEM)**
- Finite Difference Method (FDM)



A number of software packages, such as COMSOL Multiphysics, ANSYS, and MARC are available for solving problems involving CFD.

**In our study, COMSOL Multiphysics was used to carry out the simulations.**

# How FEM Works



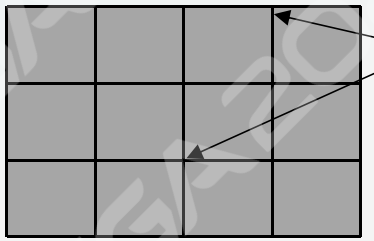
- FEM is a numerical method used to obtain an approximate solution for a given boundary value problem

Differential Equation + BC's → **FEM** → Non-linear System of Equations $(\boldsymbol{A}(u)\boldsymbol{u} = b)$

- Non-linear systems of equations are solved by using the Newton-Raphson algorithm.
- Objective is to find the (approximate) solution $\hat{u}(x, y)$ to the boundary value problem

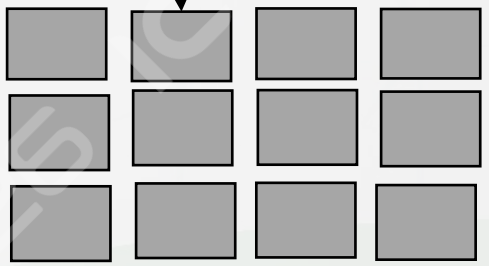


Divide into smaller pieces (Meshing)

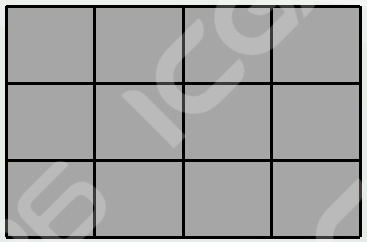


Node

Element



Perform calculations elementwise



Obtain $\hat{u}$ at nodes for the entire domain




Obtain $\hat{u}(x, y)$ for the entire domain

**DIVIDE & CONQUER**

# Mesh Statistics and Grid Independence



| Refinement Level | N.O.E | D.O.F | $Nu_{Avg}$ | % Error |
|---|---|---|---|---|
| **Normal** | 8410 | 69851 | 14.467 | — |
| **Fine** | 9994 | 81485 | 14.541 | +0.51 |
| **Finer** | 14932 | 118823 | 14.802 | +1.80 |
| **Extra Fine** | 19016 | 149847 | 15.680 | +5.93 |
| **Extremely Fine** | 37212 | 287425 | 15.681 | +0.006 |

**Table 2.** Variation in no. of Elements (N.O.E), Degree of Freedom (D.O.F), and Average Nusselt number ($Nu_{Avg}$) for various refinement levels.

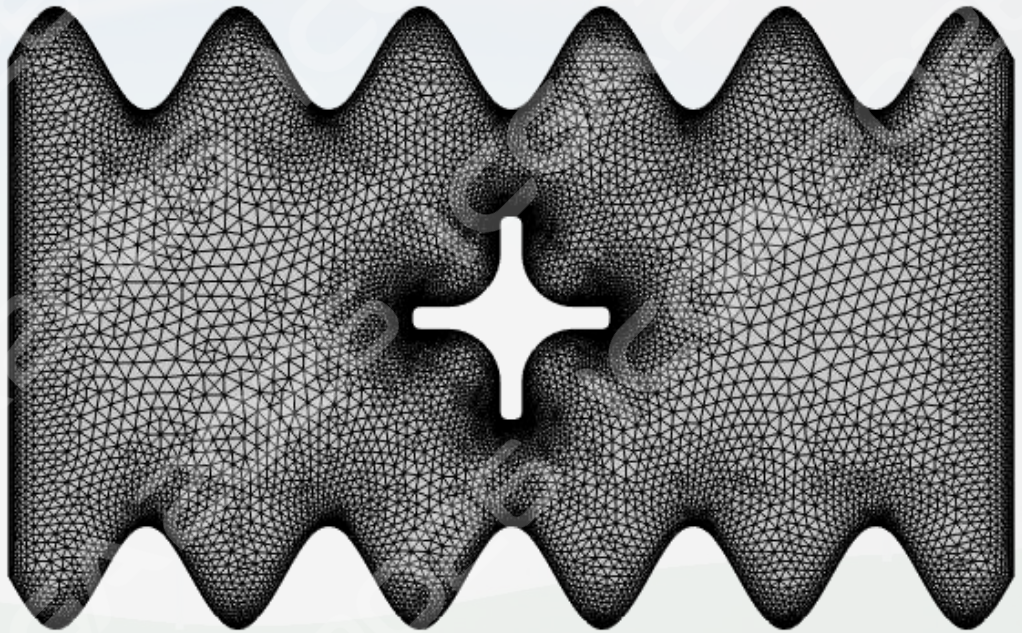


**Fig. 2.** Discretization at Extra Fine.

# Results and Discussion



## Qualitatively

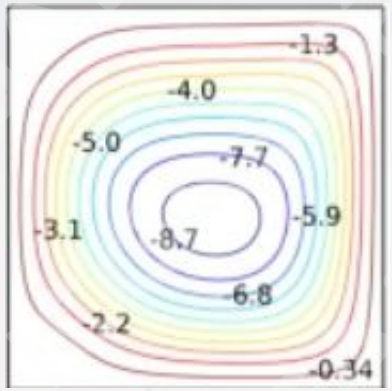
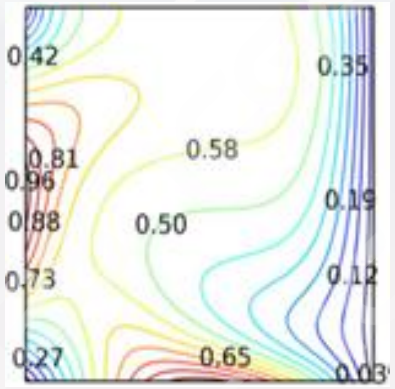
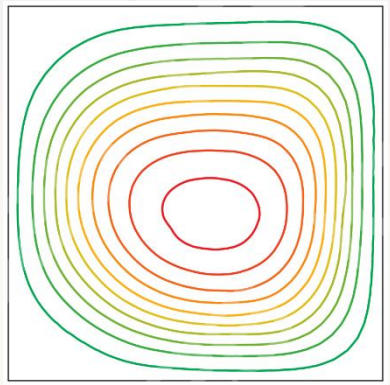
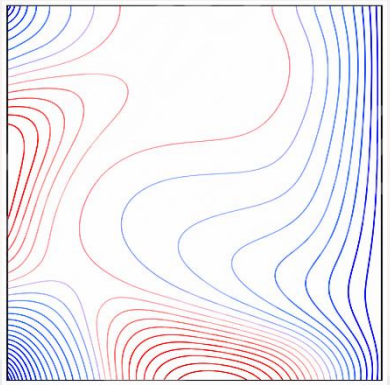
| | Streamlines | Isotherms |
|---|---|---|
| Abdel-Nour et al. [4]. |   |   |
| Present Work. |  |  |

**Fig. 3.** Comparison of the streamlines and isotherms of the current study with Abdel-Nour et al. [4] in a square cavity.

# Quantitatively



| | $Nu_{Avg}$ | | |
|---|---|---|---|
| **Da** | **Abdel-Nour et al. [4]** | **Current work** | **Error (%)** |
| $10^{-4}$ | 3.10 | 3.13 | +0.97 |
| $10^{-3}$ | 3.12 | 3.18 | +1.28 |
| $10^{-2}$ | 3.23 | 3.28 | +1.54 |

**Table 3.** Comparison of ($Nu_{Avg}$) with Abdel-Nour et al. [4] in a square cavity at (Ra=$10^5$, $\varepsilon = 0.04$, Ha=0, and $\varphi = 0.04$).

# Results and Discussion



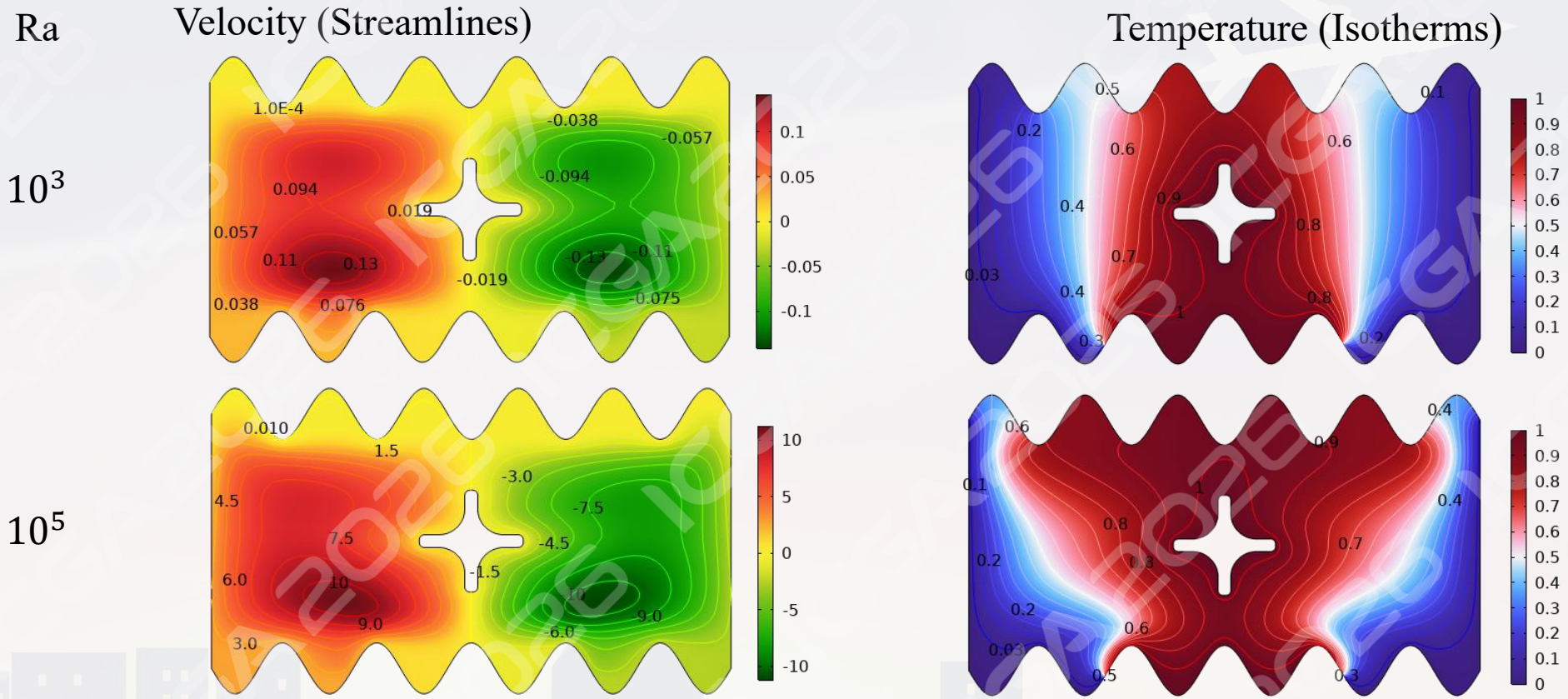



**Fig. 4.** Variations in velocity and temperature profiles against Rayleigh number (Ra).

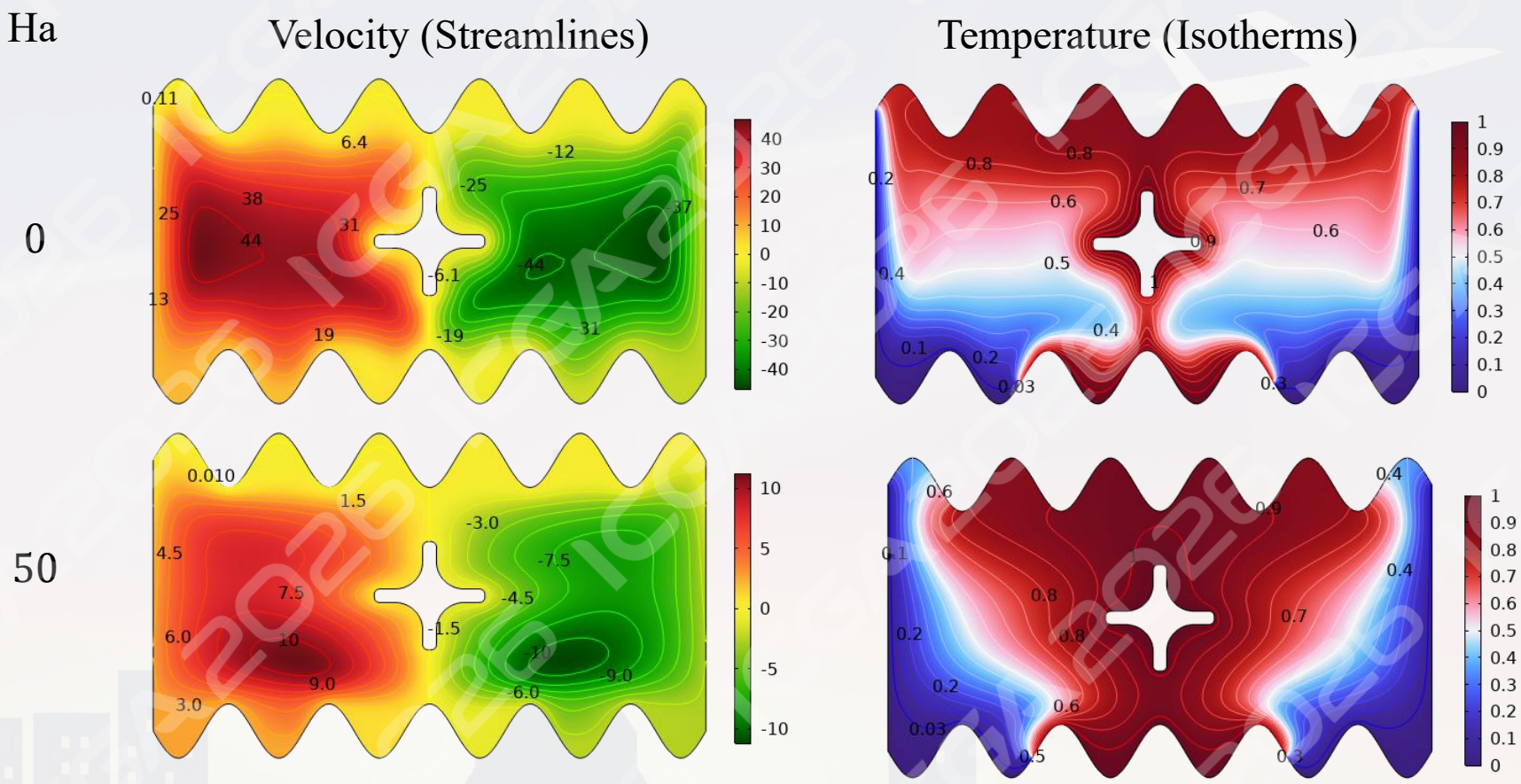



**Fig. 5.** Deviations in velocity and temperature profiles against Hartmann number (Ha).

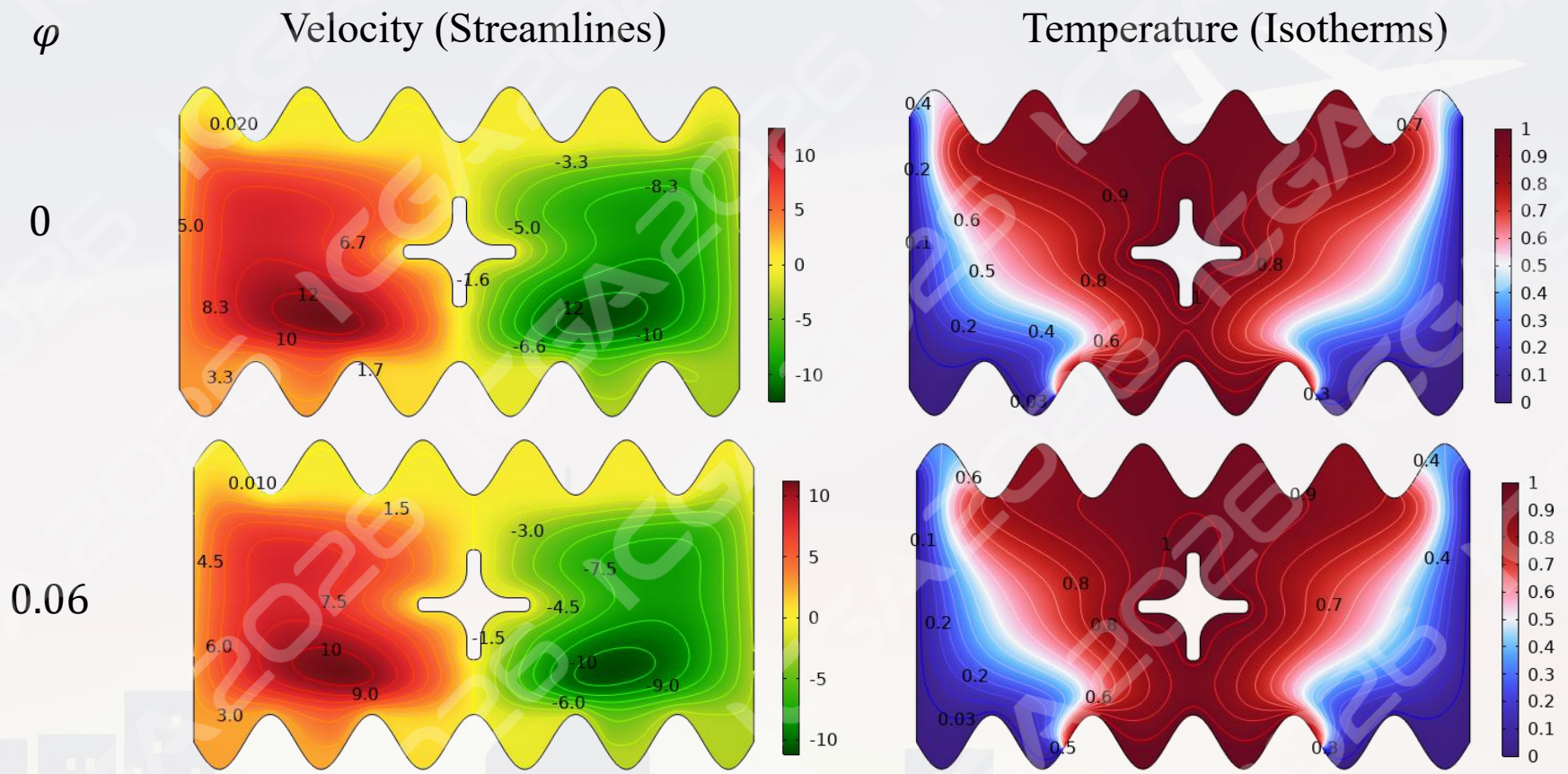



**Fig. 6.** Variations in velocity and temperature profiles against volume fraction of ternary nanoparticles ($\varphi$).

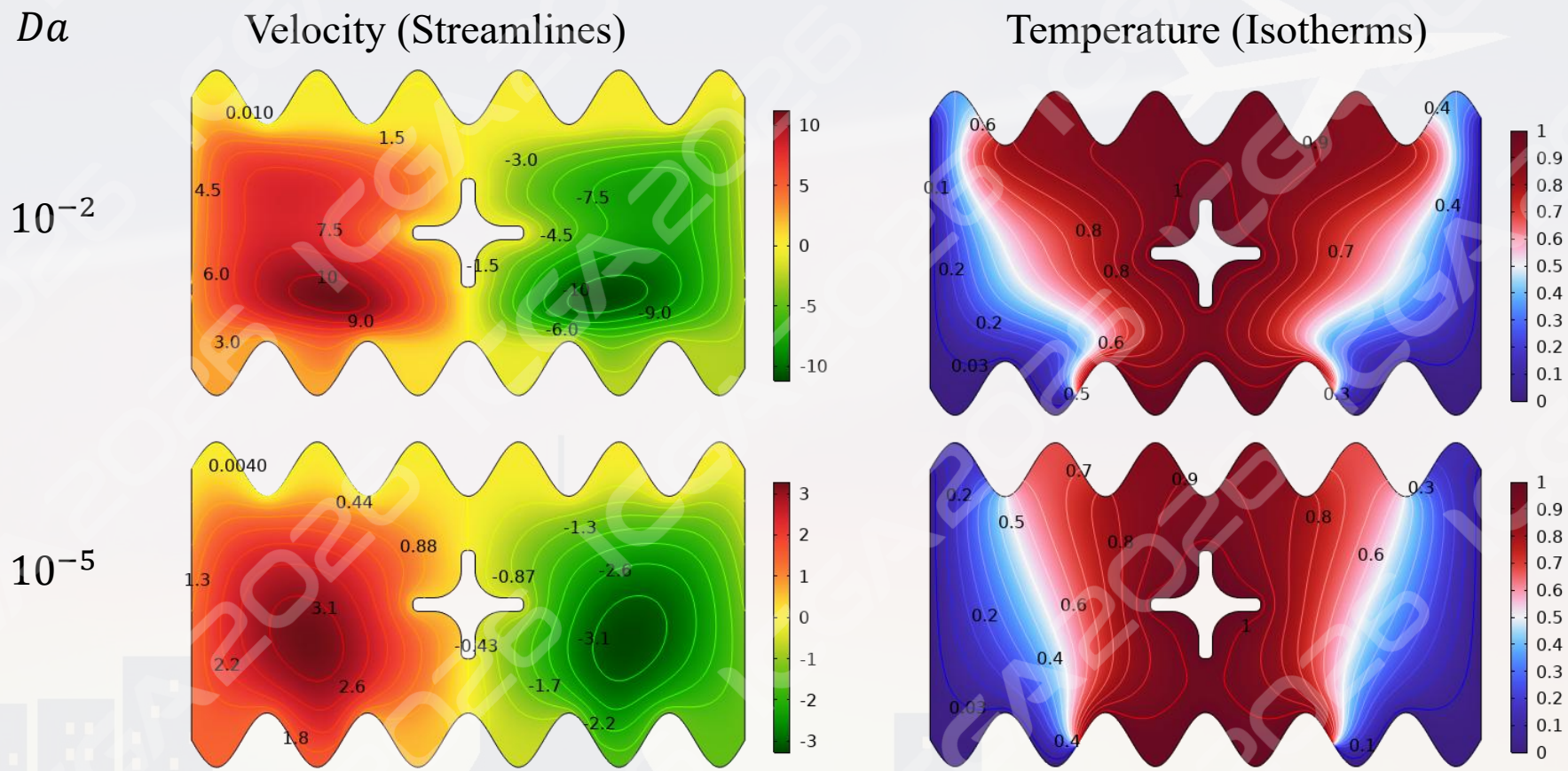



**Fig. 7.** Deviations in velocity and temperature profiles against Darcy number (Da).

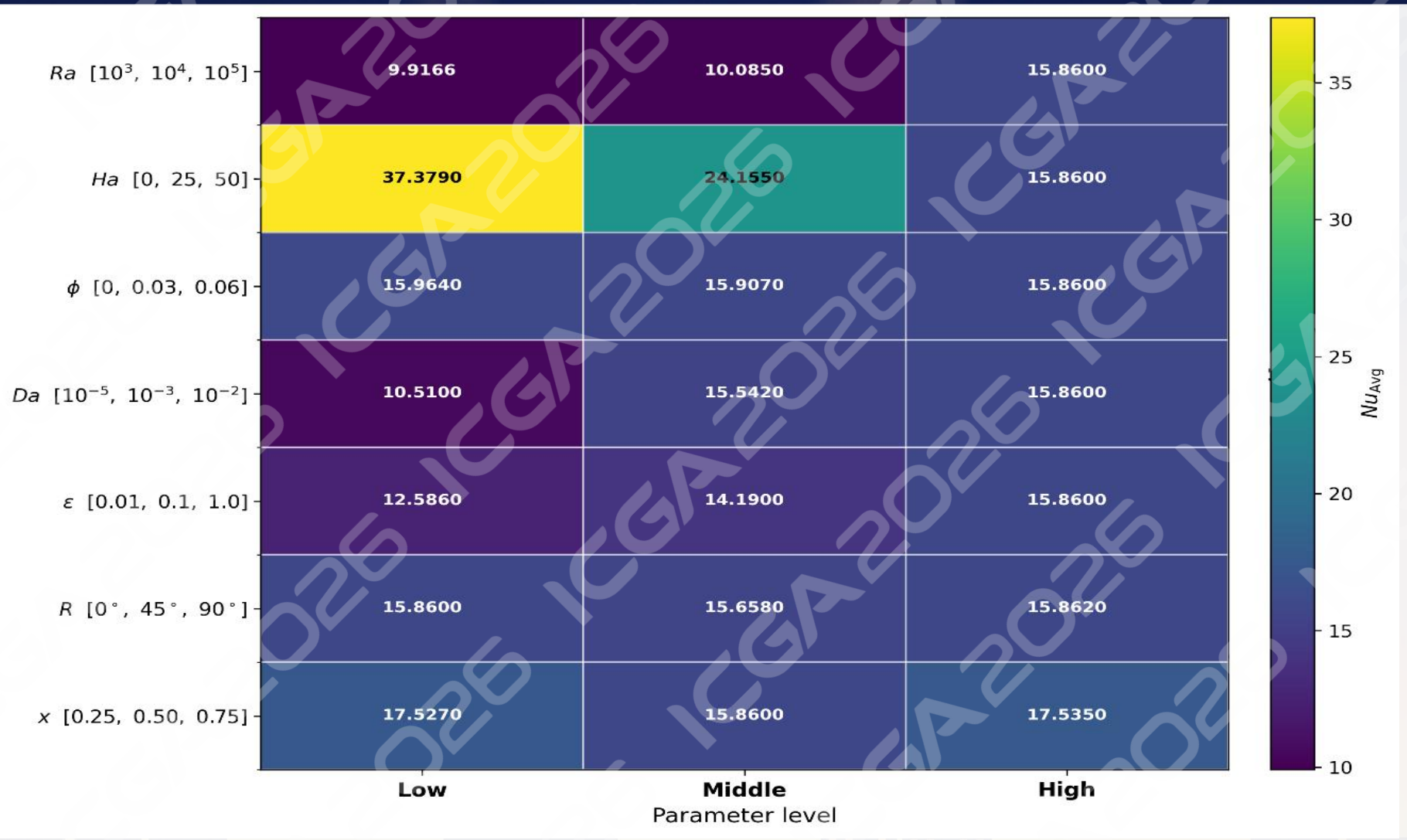



**Fig. 10.** Heat map graph of average Nusselt number ($Nu_{Avg}$) with the governing parameters (Ra, Ha, $\varphi$, Da, ε, R, $x$).

# CONCLUSIONS



1. **Buoyancy is the main driver of heat transfer:** Raising Ra from $10^3$ to $10^5$ shifts the regime from conduction to convection. $Nu_{Avg}$ rises by about 60%, so heat transfer increases.
2. **The magnetic field acts as a brake:** Ha = 0 → 50 cuts peak velocity to about a quarter and $Nu_{Avg}$ drop by about 58%. The Hartmann number can therefore be used as a passive control of heat transfer.
3. **Nanoparticle loading has a small effect here:** $\varphi$ = 0 → 0.06 slightly lowers $Nu_{Avg}$ (−0.65%). The extra viscosity cancels most of the gain in conductivity in this buoyancy-dominated regime.
4. **The porous medium has a permeability threshold:** For Da ≥ $10^{-3}$, the flow is buoyancy- and Brinkman-controlled and results change little. At Da = $10^{-5}$, the system becomes conduction-dominated. Lower porosity likewise suppresses convection, lowering $Nu_{Avg}$ by about 21% from ε = 1 to 0.01.
5. **Cylinder position matters more than orientation:** Shifting the heater off-center ($x$ = 0.25 or 0.75) raises $Nu_{Avg}$ by about 10.5%. At $x$ = 0.75, heat transfer improves, which is the most favorable combination found. Rotation has almost no effect (the 0° and 90° cases are identical by symmetry).

# Relevance to Green Aviation



*How this study connects to the theme of ICGA 2026*

1

## Cooler, safer aerospace systems

Corrugated, porous enclosures filled with magnetically controlled nanofluids model the heat-removal parts of aircraft systems, such as heat exchangers and electronics cooling.

2

## Efficiency means less fuel and fewer emissions

Better heat transfer allows lighter, more compact cooling hardware and less energy spent on cooling, which supports the goals of green aviation.

3

## Design levers from this study

Buoyancy (Ra) strengthens heat transfer. The magnetic field (Ha) acts as a brake. Permeability (Da) and heater position tune the flow. Nanoparticle loading has only a small effect.

**Outlook:** *these are computational model results; applying them to specific aircraft hardware needs further validation.*

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# Thank you

*Questions and discussion are welcome*

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