13ème Conférence Internationale des Energies Renouvelables (CIER-2025) 10.051103/PET.2601967022

Proceedings of Engineering & Technology -PET Vol 96, pp.160-167 **Advances in Energy Transition and Environmental Impacts**

Numerical Analysis of Magnetohydrodynamic Nanofluid Flow in a Corrugated Channel with an Elliptical Porous Block

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Abstract- A numerical study on 2D magnetohydrodynamic forced convection is conducted in a multi-compartment channel, including divergent, straight, and convergent sections. The working fluid is a water-MWCNT nanofluid, and the channel walls are kept at a uniform hot temperature. A technique combining corrugated walls and an elliptical porous block positioned on the center line of the first compartment exit (exit of the divergent) is adopted to enhance heat exchange and reduce pressure drop. The nanofluid flow in the porous region is described by using the general Darcy-Brinkman-Forchheimer model. The finite element method is employed to solve the governing equations and associated boundary conditions. The parametric study is focused on the influence of the permeability of the block ($10^{-6} \leq Da \leq 10^{-1}$) and the strength of magnetic field ($0 \leq Ha \leq 50$). According to the findings, having a porous block in the channel can enhance heat transfer and decrease pressure drop, resulting in better efficiency. the intensification of the magnetic field delays the flow and improves heat transfer.

Keywords: Magnetohydrodynamic; Multi-compartment channel; Elliptical porous block; Nanofluid; wavy walls.

I. INTRODUCTION

Forced convection in the presence of porous obstacles through channels with corrugated walls and in the presence of a magnetic field, represents a complex multidisciplinary field of study combining fluid dynamics, heat transfer and electromagnetism. This combination is found in various practical applications related to thermal management in advanced cooling systems in special propulsion, in nuclear reactors or simply in cooling devices for power electronic components. In a numerical study based on the Boltzmann method, Ashorynejad et al. [1] analyzed the effect of a uniform vertical magnetic field on the thermohydrodynamics of a nanofluid in a partially porous channel having a corrugated and thermally insulated bottom wall, while the top wall is flat and subjected to a uniform heat flux. A porous layer of thickness Hp placed on the hot wall is modeled using the Brinkman-Forchheimer model. The effects of active parameters such as solid volume fraction of nanoparticles, pressure gradient, magnetic field, and permeability of the porous layer, on the thermohydrodynamics of the flow are examined. The results revealed that the Nusselt number is an increasing function of the volume fraction of nanoparticles, Hartmann number, pressure gradient, and Darcy number, although the effect of Darcy numbers and pressure gradient on the temperature profile is more noticeable than others. In a scientific paper by Job et al. [2], the mixed convection of a magnetite (Fe_3O_4)-water nanofluid through a corrugated channel containing porous blocks in the presence of a non-uniform oscillating magnetic field with magnetohydrodynamic (MHD) and ferrohydrodynamic (FHD) effects was studied. The magnetic field is produced by two current-carrying wires, which are placed at fixed positions outside the channel. In this study, they used a two-phase model that considers the effects of thermophoretic diffusion and Brownian motion on the concentration of nanoparticles in the fluid.

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They found that the average pressure drop is reduced by increasing ϕ_0 and decreasing St, Mn and Ha. The average Nusselt number increases as Mn and Ha increase and d_s decreases. In a research study conducted by Hatami et al. [3], the forced laminar convection of Cu-water nanofluid in a divergent corrugated channel comprising a rotating cylindrical vortex generator was analyzed using the finite element method. The upper boundary of the channel is at low temperature while the lower boundary and the cylinder wall are at high temperature. As a main result, among all the studied parameters (Re, u, ϕ et r), increasing the Re number has the most effect on the heat transfer. An extensive numerical study on the flow of Casson fluid in mixed convection MHD through a corrugated wall channel and in the presence of a solid circular obstacle was conducted by Afraz Hussain Majeed et al. [4]. In their investigation it was observed that the drag and lift coefficients show a decreasing trend with the magnetic parameter M. The introduction of a porous medium saturated by a hybrid Al_2O_3-Cu/water nanofluid in an opened, inclined cavity, subjected to a magnetic field and having hot and cold heat sources with thermal radiation effect was the interest of the study carried out by Hossam A. Nabwey et al. [5]. One of the side walls of the cavity was irregular in shape and the center of the latter is occupied by a solid square-shaped obstacle. The numerical results obtained at the end of this study reveal that the increase in porosity increases the average Nusselt number and the distribution of isotherms is slightly reduced for the highest value of the Hartman number. Bahram Jalili et al. [6] investigated the unsteady MHD mixed convection through an asymmetric corrugated channel exposed to thermal radiation effect. Their unique solution method showed reliability despite the complexity of the problem studied. They concluded that changing the corrugated wall frequency and Peclet number will only affect the temperature component while increasing the Hartmann number, the form factor of the porous medium and the radiation parameter will significantly reduce the fluid velocity.

Through this bibliographic synthesis, we realized that there is no work that has been undertaken on a physical system like ours, moreover, few studies have considered that the magnetic field is applied to a localized area of the study system. Such a study can find a practical interest in the cooling systems of high-performance electronic components where there is the possibility of the emission of residual magnetic field. The study of MHD forced convection of a nanofluid in a multi-compartment channel in the presence of porous obstacles and corrugated walls is a cutting-edge research topic, offering opportunities for significant innovations in various technological and industrial sectors.

II. NUMERICAL METHODS

The problem considered in this study consists in studying the stationary, two-dimensional forced convection of a nanofluid based on multi-walled carbon nanotubes in a multi-compartment channel (divergent-straight channel-convergent) with corrugated walls, of length (L/H=15), of channel inlet diameter H = 1, with a convergence and divergence inclination of β = 20°. The spatial functions defining the wall undulations are given as follows: F(x)= 1- Amp (1- cos (2πn)) for the upper wall and F(x)= Amp (1- cos (2πn)) for the lower wall. It is noted that the walls are maintained at a hot temperature T_h. An obstacle in the form of an elliptical porous block is positioned at the outlet of the divergent compartment and a localized magnetic field is applied as shown in **Figure 1**.

The nanofluid MWCNT/Water enters at a uniform Velocity u_i and uniform temperature T_i. The nanofluid is assumed to be laminar, incompressible, and Newtonian, with constant physical properties. The single-phase homogeneous model was used to model the nanofluid flow with flow through the porous medium described by the Darcy-Brinkman-Forchheimer model. Viscous dissipation was neglected and heat dissipation by Joule effect is taken into consideration.

In order to present the equations in their dimensionless form, we use the following variables:

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$$(X,Y) = \frac{(x,y)}{H};\ (U,V) = \frac{(u,v)}{U_i}; P = \frac{p}{\rho_{nf} U_i^2}; \theta = \frac{T - T_i}{T_h - T_i}$$

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

Momentum:
$$\frac{1}{\delta_1 \varepsilon^2}\left[U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y}\right] = -\frac{\partial P}{\partial X} + \frac{\rho_f}{\rho_{nf}}\frac{\mu_{nf}}{\mu}\frac{R_\mu}{Re}\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}\right) - \frac{\rho_f}{\rho_{nf}}\frac{\mu_{nf}}{\mu}\frac{1}{Re\,Da}U\delta_2 - \frac{C}{\sqrt{Da}}|\vec{V}|U\delta_2 - \frac{\varepsilon Ha^2}{Re}\frac{\sigma_{nf}}{\sigma_f}\frac{\rho_f}{\rho_{nf}}U \quad (2)$$

$$\frac{1}{\delta_1 \varepsilon^2}\left[U\frac{\partial V}{\partial X} + V\frac{\partial V}{\partial Y}\right] = -\frac{\partial P}{\partial Y} + \frac{\rho_f}{\rho_{nf}}\frac{\mu_{nf}}{\mu}\frac{R_\mu}{Re}\left(\frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2}\right) - \frac{\rho_f}{\rho_{nf}}\frac{\mu_{nf}}{\mu}\frac{1}{Re\,Da}V\delta_2 - \frac{C}{\sqrt{Da}}|\vec{V}|V\delta_2$$
(3)

Energy:
$$U\frac{\partial \theta}{\partial X} + V\frac{\partial \theta}{\partial Y} = \frac{(\rho C_p)_f}{(\rho C_p)_{nf}}\frac{R_k}{RePr}\frac{k_{nf}}{k_f}\left[\frac{\partial^2 \theta}{\partial X^2} + \frac{\partial^2 \theta}{\partial Y^2}\right] + \varepsilon Ec\frac{Ha^2}{Re}\frac{\sigma_{nf}}{\sigma_f}\frac{(\rho C_p)_f}{(\rho C_p)_{nf}}U^2 \quad (4)$$

We take the constants $\delta_1 = \delta_2 = 1$; ε =0.97 and C=0.1 at the elliptical porous block
We take the constants $\delta_1 = \frac{1}{\varepsilon^2}$ et $\delta_2 = 0$; $\mu_{eff} = \mu_{nf}$ and $k_{eff} = k_{nf}$ at the nanofluid region.

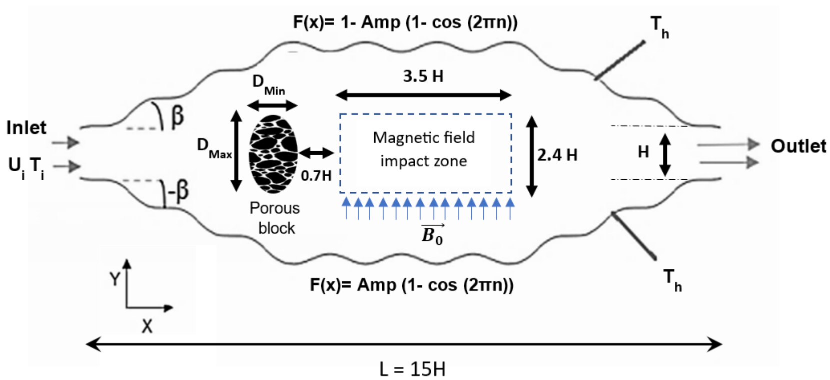

Fig. 1 Physical domain

The dimensionless numbers apparent in the equations are:
$Re = \frac{U_e \rho_f H}{\mu_f}$; $Pr = \frac{\mu_f C_{pf}}{k_f}$; $Da = \frac{K}{H^2}$; $R_\mu = \frac{\mu_{eff}}{\mu_{nf}}$; $R_k = \frac{k_{eff}}{k_{nf}}$; $Ha^2 = \frac{\sigma_f B_0^2 H^2}{\mu}$; $Ec = \frac{U_i^2}{C_{pf}\,\Delta T}$The governing equations are solved in conjunction with the following boundary conditions:

- Inlet: $V = 0; U = 1; \Theta = 0$
- Wall: $\Theta = 1 ; U = V = 0$
- Outlet: $V = \frac{\partial U}{\partial X} = \frac{\partial \theta}{\partial X} = 0 ; P = 0$

The Nusselt number is mainly used to evaluate the heat exchanges taking place between a wall and a fluid. It is defined as follows:

$$Nu_{Low,Up} = \frac{hD}{k_f} = \frac{k_{nf}}{k_f}\frac{\partial \theta}{\partial \eta}\bigg|_{Low,Up} \quad (5)$$

The temperature gradient on the wavy walls is defined by:

$$\frac{\partial \theta}{\partial \eta} = \sqrt{\left(\frac{\partial \theta}{\partial X}\right)^2 + \left(\frac{\partial \theta}{\partial Y}\right)^2} \quad (7)$$

$$Num_{Low,Up} = \frac{1}{s}\int_0^S Nu_{Low,Up}\ ds \quad (8)$$

s is the curvilinear length of the corrugated wall $Nu_{Av} = \left(Num_{Low} + Num_{Up}\right)/2$ (9)

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The pressure drop is calculated by the following formula $\Delta P = \frac{P_{m(X=0)} - P_{m(X=L)}}{L}$ (10)

A Performance Evaluation Coefficient is used to compare heat transfer improvements to pressure drop losses. It is defined as:

$$PEC = \frac{\left(Nu_{Av}/(Nu_{Av})_{ref}\right)}{\left(\Delta P/\Delta P_{ref}\right)^{1/3}}$$

the reference case corresponds to a multi-compartment channel with corrugated walls without an obstacle and without a magnetic field

III. RESULTS AND DISCUSSION

In this work, several parameters have been studied, in order to improve the heat transfer in our system. To simplify the study, some control parameters have been fixed and others diversified. For this, the wave amplitude (Amp = 0.1) and the waves number (n = 9), the volume fraction of nanoparticles (ϕ = 0.3%), The Reynolds number (Re=250), the ratio of thermal conductivities and dynamic viscosities (Rk = Rμ = 1) and the aspect ratio of the porous obstacle (R_f = 1.5) was fixed. It is noted that the Prandtl number (Pr) and Eckert number (Ec) have been calculated for each execution. A convergence criterion of 10^{-6} is selected, which ensures converged solutions for different parametric studies. On the other hand, the following parameters have been varied: The Darcy number ($10^{-6} \leq Da \leq 10^{-1}$) and the Hartmann number ($0 \leq Ha \leq 50$).

Figure 2 provides an in-depth analysis of the evolution of streamlines and temperature distribution as a function of the permeability of the porous block (Figure 2a) and the intensity of the magnetic field (Figure 2b). The overall results highlight the complex interaction between convection, diffusion, and magnetic damping, thereby offering a clearer characterization of the coupled flow and heat-transfer dynamics within the cavity. As the Darcy number increases, the permeability of the porous block becomes higher, which decreases the internal resistance to fluid motion and gradually makes the behavior of the porous medium resemble that of a free fluid. Under these conditions, the nanofluid penetrates more easily into the porous structure, enhancing hydrodynamic continuity between the two regions and promoting a more uniform thermal distribution. Conversely, when the Darcy number decreases, the permeability is strongly reduced and the porous block behaves increasingly like a solid obstacle, imposing a significant deviation of the flow. Streamlines concentrate around the block edges, and convective cells become fragmented, leading to reduced internal thermal diffusion. For Da = 10^{-6}, the medium becomes nearly impermeable, causing heat transfer to occur mainly along the block boundaries, while the flow bypasses the obstacle and generates pronounced hydrodynamic gradients accompanied by peripheral recirculation.

The influence of the Hartmann number, illustrated in Figure 2b, reveals a notable structural modification of the flow field under the action of the magnetic field. Increasing the magnetic intensity enhances the Lorentz force, which acts directly against the motion of the nanofluid and introduces significant dissipation in the region where the field is applied. This effect results in a substantial reduction of flow velocity, a weakening of local vortices, and a progressive stabilization of the streamlines. Simultaneously, the flow is redirected toward the corrugated walls regions less affected by magnetic resistance leading to local acceleration of the fluid and an intensification of convective heat transfer. The spatial redistribution of velocity and isotherms confirms that the interaction between the magnetic field and the porous medium simultaneously influences convective and conductive mechanisms, thereby altering the global thermal topology of the cavity. Overall, the combination of variable permeability and an imposed magnetic field leads to a complex reconfiguration of the flow and heat-transfer fields. These findings underscore the sensitivity of the system to the physical properties of the porous medium and

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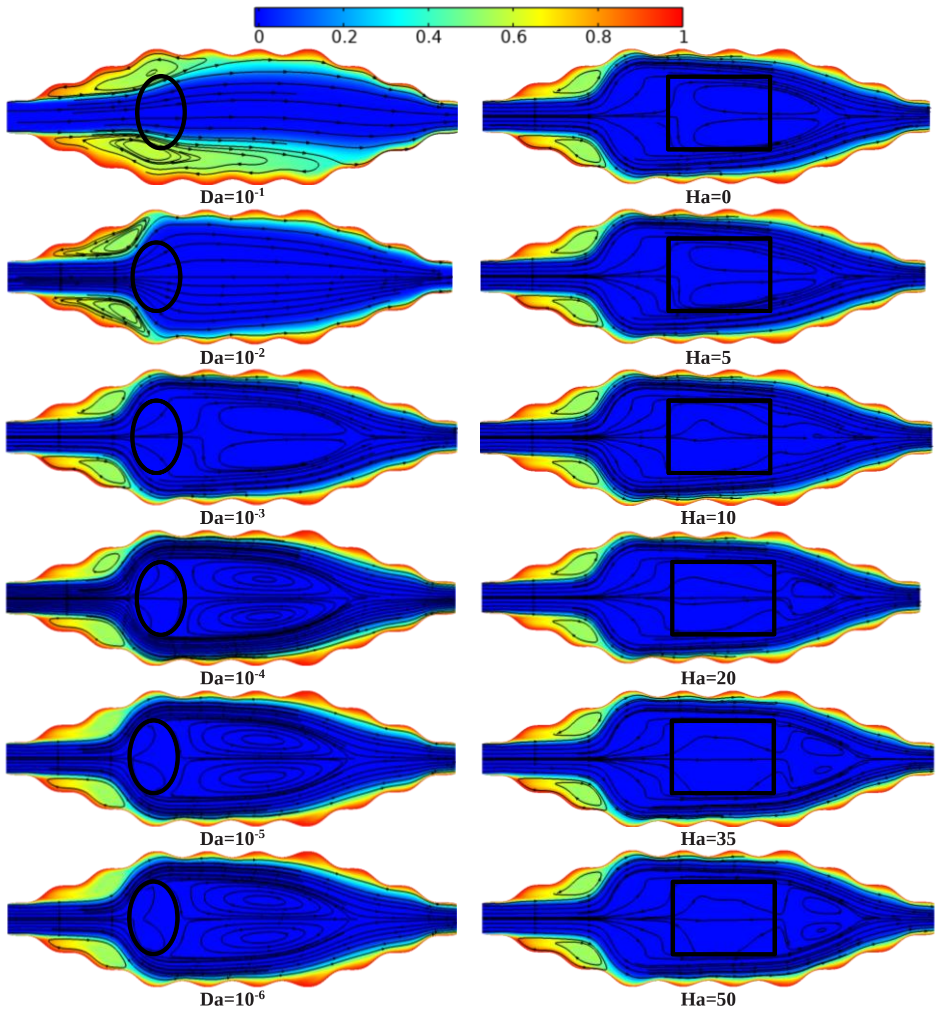
to magnetic control conditions, offering valuable perspectives for the optimization of advanced thermal management devices.



(a) Permeability effect of the porous block

(b) MHD effect of the area subjected to the magnetic field

Fig. 2 Temperature field and streamlines- (a) for different Da numbers at Ha=0.- (b) for different Ha numbers at Da=10^{-3}.

The PEC is a dimensionless parameter that quantifies the overall efficiency of the system by relating the heat transfer rate to the required pumping power. Figure 3 illustrates the variation of PEC as a function of the Darcy and Hartmann numbers, providing an integrated view of the combined effects of porous block permeability and magnetic field intensity on the thermohydraulic performance. The results indicate that as the permeability of the porous block decreases down to Da = 10^{-4}, the PEC increases significantly. This trend reflects an optimized balance between thermal transport and flow resistance: the block becomes less permeable, which limits internal flow, but enhances heat recovery through convection in peripheral regions, thereby improving overall efficiency. For Da values below 10^{-4}, the PEC stabilizes and its variation becomes negligible, suggesting that further reductions in permeability have little impact on the ratio of heat transfer to pumping power. Regarding the Hartmann effect, the results show that increasing the magnetic field intensity enhances the PEC, particularly for high-permeability blocks. This improvement is attributed to the stabilizing action of the Lorentz force on the flow,

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which reduces hydrodynamic losses while maintaining effective heat transfer. Consequently, the application of a magnetic field can be considered an effective strategy for optimizing thermohydraulic performance, especially in configurations with relatively high porous medium permeability. In summary, the PEC analysis highlights that the overall performance of the system strongly depends on the interplay between permeability and magnetic field intensity. Appropriate tuning of these parameters allows for simultaneous enhancement of heat transfer and minimization of pumping energy, offering valuable guidance for the design of efficient thermal management systems.

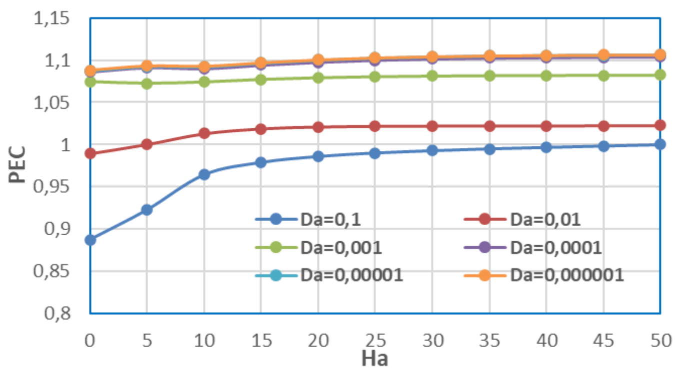

Fig. 3 Evolution of the PEC for different Darcy numbers and magnetic field strengths.

V. CONCLUSION

The work carried out made it possible to study of the MHD forced convection two-dimensional, laminar and incompressible of a nanofluid (MWCNT/water) which develops in a multi-compartment channel (Divergent-Straight Channel-Convergent) with corrugated walls and a porous block. Based on simplifying assumptions, the physical phenomenon studied is simplified then formulated mathematically through the equations of mass, momentum and conservation of energy. The resulting system of equations with the associated boundary conditions is solved by the finite element method. This study allowed us to highlight the following points:

- When the Darcy number increases, the permeability is greater and the behavior of the porous block approaches the fluid behavior. On the other hand, for low values of the Darcy number, the block forms an obstacle which acts as a single solid phase.
- Concerning the magnetohydrodynamic (MHD) effect, we can say that the heat transfer is improved with the Hartmann number where the Lorentz force imposes its dominance notably at high permeabilities.

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ISSN: 1737-9334