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Numerical Modeling of the Effect of Magnetic Field Direction on Magnetoconvection of a Newtonian Fluid Confined Between Two Vertically Eccentric Hemispheres

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ABSTRACT

This work consists in numerically studying the effect of the magnetic field direction on the phenomenon of heat transfer by laminar natural convection of an electrically conductive Newtonian fluid. Our study model is a hemispherical cavity delimited by two vertically eccentric hemispheres. A heat flux of constant density is imposed on the inner hemisphere while the outer hemisphere is maintained at a constant temperature. The combination of thermal and electrical boundary conditions is exploited to obtain the critical values of the parameters marking the onset of instability. The Boussinesq approximation is used to study the equations governing this fluid instability. The projection of these equations into the bispherical coordinate system and the discretization by the finite difference method facilitated the development of a Fortran computer code. Exploitation of this code made it possible to determine the growth rates for different inclination angles. The Rayleigh number, the Hartmann number, the eccentricity and the ratio of the radii remain fixed. Thus, the direction of the magnetic field has an effect on the magneto-convective transfer. The inclination of the magnetic field modifies the convection currents and therefore the heat transfer efficiency. The higher the inclination, the more convection is affected and the heat transfer becomes less efficient. This can result in an increase in the Nusselt number and a decrease in the minimum current function.At the end of the study, the results obtained are consistent and revealing: they are in good agreement with those of references taken from the literature.

Keywords: Magnetoconvection; Magnetic field; Hemispherical cavity; Eccentricity; Rayleigh number; Hartmann number; Nusselt number.

1. INTRODUCTION

The phenomenon of magnetoconvection, which describes the convective displacement of an electroconductive fluid subjected to both convection and magnetic forces, has been the subject of numerous studies in recent decades [1-2]. These materials are of interest due to their implications in many natural and applied phenomena [3]. According to [4], magnetoconvection has various applications in fields such as geophysics, astrophysics, plasma physics, missile technology, medicine and biology, among others. Consequently, many experimental and numerical studies have been carried out on the magneto-convection of a fluid confined in enclosures of various configurations, in parallel with studies on pure natural convection [5]. These enclosures often have varied geometries, which can be parallelepiped [6-7], cylindrical [8-9] or even spherical [10-11-12-13]. Correlations giving the Nusselt and Rayleigh numbers are sometimes proposed. An increase in these numbers, reflecting an intensification of natural convection or the magnetic field, can influence the viscosity of the fluid and the stability of the flows depending on the geometry of the walls [14-15]. In this perspective, magneto-convection modeling studies have shown that, in addition to stabilizing the main convection roll, a horizontal magnetic field leads to an increase in kinetic energy and heat transfer rate compared to a study without a magnetic field [7]. In addition, a Hall effects analysis of magneto-convective instability and heat transfer conducted by [16] investigates the parameters that can influence the flow field and temperature distribution. According to the results obtained, it can be seen that Hall currents significantly reduce the flow field. The studies conducted by references [17-18] sought to obtain a comprehensive and essential understanding of the characteristics of flows and heat transfer in an enclosure in the presence of a magnetic field, demonstrating that this magnetic field reduces the heat transfer rate. The impact of the magnetic field on mixed convection with an exponential temperature distribution, as well as on internal heat and viscous dissipation, was examined by [19]. It was observed that increasing the Prandtl number decreases the skin friction coefficient, while increasing the magnetic field increases the local Nusselt number. A study by [10] investigated the transient regime of natural convection of a non-conducting Newtonian fluid between two vertical eccentric spheres, with the inner sphere exposed to a constant density heat flux and the outer sphere maintained at a constant temperature. Their results show that increasing the modified Rayleigh number allows for faster steady-state attainment, and that eccentricity has a negligible influence on the establishment of the steady state. Convective motion is amplified by positive eccentricities. Heat exchange, characterized by the Nusselt number, increases with the modified Rayleigh number. A study conducted by [20] focused on the case of a hemisphere, and the results indicate that the center of the vortex moves upward with larger eccentricities. The Nusselt number also increases with the modified Rayleigh number. As the latter increases, the temperature decreases for a given eccentricity. This vast literature highlights the importance and scientific scope of thermal convection of an electrically conducting fluid subjected to a magnetic field [21]. It is precisely with this in mind that the present study was initiated. Our study focuses on magnetoconvection and the impact of the magnetic field direction. It represents a captivating area of physics where the complex effects of natural convection and the magnetic field will be thoroughly examined. The orientation of the magnetic field plays a crucial role in modulating circulation patterns, heat transfer, and fluid instabilities. This study aims to closely explore these dynamic interactions, highlighting the significant influence of the direction of the magnetic field on magnetoconvection phenomena.

2. Material and methods

2.1. Problem formulation

Figure 1 symbolizes the motion of an electrically conductive Newtonian fluid (ionized air) subjected to a horizontal magnetic field and confined in an annular space delimited by two vertically eccentric hemispheres. The radii of the inner and outer hemispheres are designated respectively by Ri and Re. The algebraic value of the distance separating the centers of these two hemispheres is defined as the eccentricity e'. Inside and on the walls of the enclosure, the temperature is initially uniform. A heat flux (q') of constant density will be applied at the level of the inner hemisphere while the temperature of the outer hemisphere will remain constant (T'). The walls separating the two hemispheres at angles θ=0 and θ= π are adiabatic. A transient natural convection of this conductive fluid caused by the temperature difference of the two hemispheres will develop inside the domain.

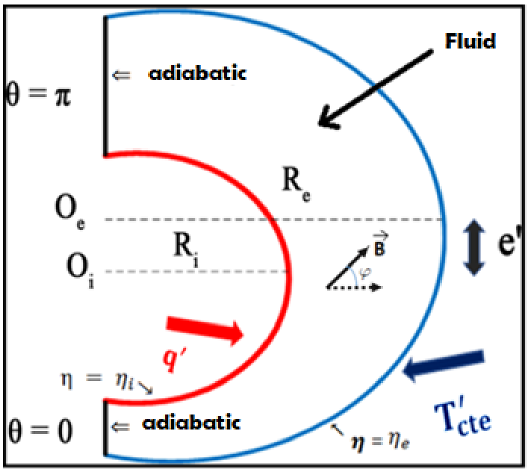

Figure 1: Geometry of the problem [2]

The physical properties of the fluid are constant except for its density in the term associated with gravity in the equation of motion where it varies linearly with temperature and obeys Boussinesq's law. The fluid is Newtonian and the flow is laminar, incompressible and two-dimensional. The magnetic field is assumed to be constant and the induced field is neglected. The viscous dissipation function, radiative effects as well as the pressure term are neglected. The boundaries of the studied system are considered to be electrically insulating. The walls of our enclosure are made up of two spherical parts and two others offset from the vertical. To translate the parietal conditions more simply, we must therefore look for a curvilinear coordinate system in which the limits of our domain are parameterized by constant coordinate lines. Thus, taking into account the geometry of the enclosure, the most appropriate coordinate system is that of bispherical coordinates. For a two-dimensional flow, the transition from Cartesian coordinates (x, y) to bispherical coordinates is given by the relation (1) :

$$x = \frac{a \sin\theta}{ch\eta - cos\theta} \; ; \; y = \frac{a \, sh\eta}{ch\eta - cos\theta} \qquad (1)$$

Along the vertical are two walls identified by θ = 0 and θ = π. The inner and outer hemispheres are represented by the coordinate lines h=hi and h=he, respectively.

After introducing simplifying assumptions, we establish the various dimensionless equations necessary to solve the problem considered in this study. The vortex-flux functions (vortex flow) are translated by the momentum and heat equations expressed by relation (2):

$$\partial_t F + A(U)\partial_\eta F + B(V)\partial_\theta F = P\left(\partial_\eta^2 F + \partial_\theta^2 F\right) + S\left(G_2\partial_\eta T - G_1\partial_\theta T\right) + R\left(\partial_\eta B_1 - \partial_\theta B_2\right) \quad (2)$$

The different values of the variables F, A, B, P, S and G are given in Table 1.

Table 2.1: Variables of the heat and vorticity equation

Equation	F	A(U)	B(V)	P	S	R
Heat	T	$\frac{1}{H}\left[U - \frac{G_2}{K}\right]$	$\frac{1}{H}\left[V + \frac{G_1}{K}\right]$	$\frac{1}{H^2}$	0	0
Movement	$\frac{\Omega}{K}$	$\frac{1}{H}\left[U - \frac{3PrG_2}{K}\right]$	$\frac{1}{H}\left[V + \frac{3PrG_1}{K}\right]$	$\frac{Pr}{H^2}$	$\frac{Ra.Pr}{KH}$	$\frac{Ha^2.Pr}{KH^2}$

With:

$$B_1 = H\left(UB_\eta B_\theta - VB_\eta^2\right);\ B_2 = H\left(VB_\eta B_\theta - UB_\theta^2\right) \quad (3)$$

$$B_\eta = \frac{B_\eta^*}{B_0} = G_2\ cos\varphi + G_1\ sin\varphi\ ;\ B_\theta = \frac{B_\eta^*}{B_0} = G_2\ sin\varphi - G_1\ cos\varphi \quad (4)$$

Where the quantities U, V, G1, G2, K, H, are defined by equations (5), (6) and (7)

$$U = \frac{1}{HK}\,\partial_\theta\Psi\ ;\ V = -\frac{1}{HK}\,\partial_\eta\Psi \quad (5)$$

$$G_1 = \frac{1-\cos\theta \mathrm{ch}\eta}{\mathrm{ch}\eta-\cos\theta}\ ;\ G_2 = -\frac{\sin\theta \mathrm{sh}\eta}{\mathrm{ch}\eta-\cos\theta} \quad (6)$$

$$K = \frac{asin\theta}{D(ch\eta-cos\theta)}\ ;\ H = \frac{a}{D(ch\eta-cos\theta)} \quad (7)$$

The incompressibility condition is verified by the equation of the stream function is given by the relation (8):

$$\Omega = \frac{1}{K^2H}\left(G_2\partial_\eta\Psi - G_1\partial_\theta\Psi\right) - \frac{1}{KH^2}\left(\partial_\eta^2\Psi + \partial_\theta^2\Psi\right) \quad (8)$$

In addition to these different equations, boundary conditions and initial conditions are added.

At t = 0, the conditions are expressed by the relation (9):

$$\Omega=\Psi=T=U=V=0 \quad (9)$$

At t > 0, the boundary conditions are translated by equations (10), (11) and (12) according to the wall.

- On the inner spherical wall (η = ηi)

$$\Psi = U = V = 0\ ;\ \Omega = -\frac{1}{KH}\partial_\eta^2\Psi\ ;\ \partial_\eta T = H_i = \frac{ch\eta_i}{sh^2\eta_i} \quad (10)$$

- On the outer spherical wall (η=ηe)

$$\Psi = U = V = T = 0\ ;\ \Omega = -\frac{1}{KH}\partial_\eta^2\Psi \quad (11)$$

- On the two vertical walls (θ = 0, θ = π)

$$\Psi = U = V = 0\ ;\ \partial_\eta T = 0\ ;\ \Omega = -\frac{1}{KH}\partial_\theta^2\Psi \quad (12)$$

The Nusselt number can be translated as the thermal energy transmitted by a spherical wall. The local Nusselt numbers Nu and average ($\overline{Nu}$) are defined by relations (13) and (14) as a function of the wall.

- For the inner spherical wall

$$Nu_i = \frac{1}{T_{i,m}} \; ; \; \overline{Nu_i} = \frac{1}{S_i}\int Nu_i dS_i \tag{13}$$

- For the outer spherical wall

$$Nu_e = \frac{1}{H_e T_{i,m}}\partial_\eta T \; ; \; \overline{Nu_e} = \frac{1}{S_e}\int Nu_e d\,S_e \tag{14}$$

2.2 Numerical analysis

To develop a numerical code to stimulate the magnetoconvection of a Newtonian fluid confined in an annular space, we used:

• The implicit alternating directions (ADI) method for the time-domain solution of the momentum and heat equations;

• The finite difference method for spatial integration.

We will use the THOMAS algorithm to solve the system of linear equations obtained by the ADI method. However, for the flow function equation, the solution is based on the successive overrelaxation (SOR) method with an optimal relaxation parameter. At the iterative loop level, the calculation result Znew of a quantity to be determined will only be considered a convergent solution if, with the old Zold value, it obeys the following relationship (15):

$$\frac{|Z_{new}-Z_{old}|_{max}}{|Z_{new}|} \leq 10^{-5} \tag{15}$$

The steady state is only reached if this relative error between two consecutive time steps for all quantities obeys the relation (16):

$$\frac{|Z^{n+1}-Z^{n}|_{max}}{|Z^{n+1}|_{max}} \leq 10^{-5} \tag{16}$$

Z^n represents Ω, Ψ or T for the n^{th} time step.

3. Results and discussion

In this section, we will discuss the results obtained by numerical simulations in order to better understand the effect of the inclination of the magnetic field on the magneto-convective flow.

3.1. Calculation conditions

Tests carried out on the influence of the mesh and the time step lead us to choose the 51 x 51 mesh and the 10^{-4} time step. We therefore present the results of these tests in Tables 1 and 2. These results prove that our choices constitute, among other things, a good compromise.

Table 3.1: Effects of time steps on the Nusselt number of the thermal wall for Ha=1, Ra=10^5, e=0, Δt=10^{-4} and the grid system is 51x51

	Time steps		
	10^{-3}	**10^{-4}**	**10^{-5}**
Nu	4.7337	4.7298	4.7296
Difference (%)	0.087	0.004	0
Time computing (min)	5	124	802

Table 3.2: Effets du raffinement du maillage sur le nombre de Nusselt de la paroi thermique pour Ha=1, Ra=10^5, e=0 et Δt=10^{-4}

	Mesh grid							
	21*21	**21*41**	**41*41**	**41*51**	**41*81**	**51*51**	**51*81**	**81*81**
Nu	4.8750	4.8871	4.7515	4.7503	4.7502	4.7298	4.7297	4.7060
Difference (%)	3.59	3.85	0.97	0.94	0.94	0.51	0.50	0
Time computing (min)	9	97	225	261	362	348	447	604

3.2. Validation

For a zero magnetic field, the problem becomes that of laminar natural convection. The results presented in Table 3 provide information on the values of the average Nusselt number, calculated and then given for different Rayleigh numbers. We compared these results with those of [20] for the study of transient laminar convection between two vertically eccentric hemispheres. These comparisons show a relative difference of 2.72% for all the cases presented. This shows an excellent agreement between the results.

Table 3.3: **Comparison of the average Nusselt number in the case where e = 0**

	Ra				
	10^3	**10^4**	**10^5**	**10^6**	**10^7**
Nusselt number (our results)	2.0673	3.0379	4.8920	7.7680	11.708
Nusselt number (results of [19])	2.125	3.0651	4.982	7.6874	11.671
Difference (%)	2.72	0.89	1.81	1.05	0.32

3.4 Direction of the magnetic field

To study the influence of the direction of the magnetic field, we set the value of the Hartmann number to 10, the eccentricity to -0.5 and the Rayleigh number Ra=10^5.

3.4.1 Isothermes et isocourants

Figures 2, 3, and 4 show the temporal evolution of isotherms and isocurrents for different values of magnetic field inclination $\varphi=\{0; \pi/4; \pi/2\}$.

For a horizontal magnetic field $\varphi=0$, Figure 2 shows that the isotherms stabilize. The magnetic field increasingly suppresses convection by blocking the fluid's movement. The isotherms follow the inner spherical wall, and their directions are those of the magnetic field when they are thermally perturbed. Thanks to this stabilizing force that the magnetic field exerts on the fluid by preventing the formation of convection structures, the streamlines also follow the direction of the magnetic field, and the fluid's movement is severely limited.

If the magnetic field is vertical, i.e. $\varphi=\pi/2$, and through Figures 3, we see that the isotherms are smooth and more regular with fewer fluctuations compared to those we obtain in a pure natural convection problem [20]. We can also note an increase in the thermal stratification of the fluid which results in more spaced isotherms with more pronounced temperature gradients. Similarly, the vertical magnetic field restricts the vertical movements of the fluid, creating a "pinching" action on the streamlines. The streamlines are therefore deformed by the magnetic field, creating more concentrated convection zones or convection deficits in certain regions. This results in a convection pattern that is globally different from that which would occur in the absence of a magnetic field.

When the magnetic field is oblique, i.e. $\varphi=\pi/4$, Figure 4 shows us through the isotherms the absence of convective movements due to the effect of the magnetic field. These isotherms are more uniform and show a very significant decrease in thermal convection. As for the streamlines, the center of the vortex simply follows the direction of the flow. Here, the oblique magnetic field stabilizes the fluid and partially suppresses instabilities and fluctuations. The center of the vortex develops along the direction of the magnetic field.

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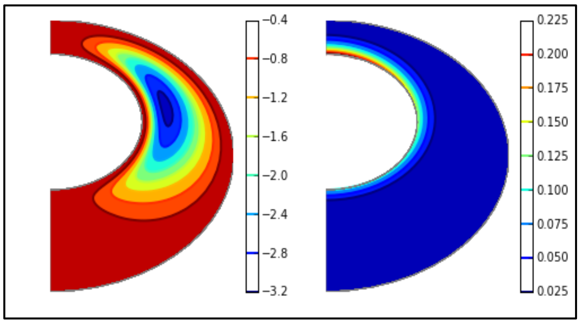
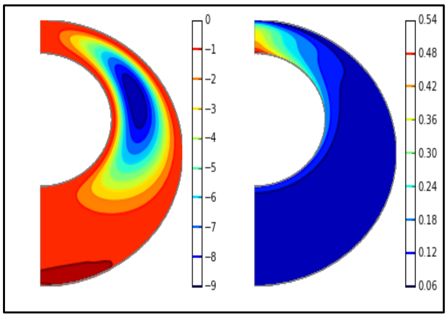
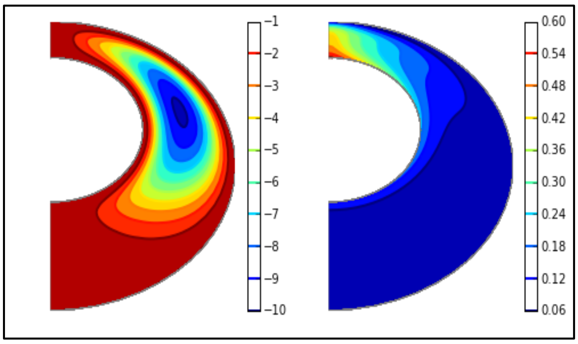
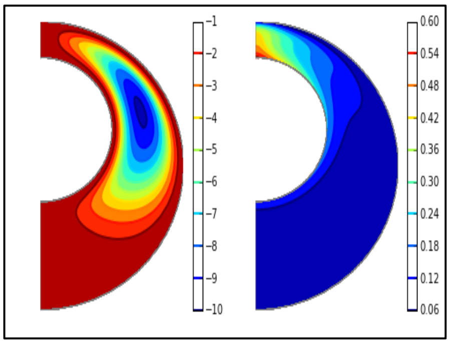




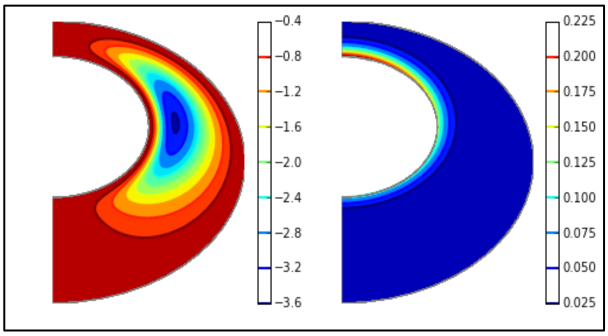
t = 2.10^{-2} t =8.10^{-2}

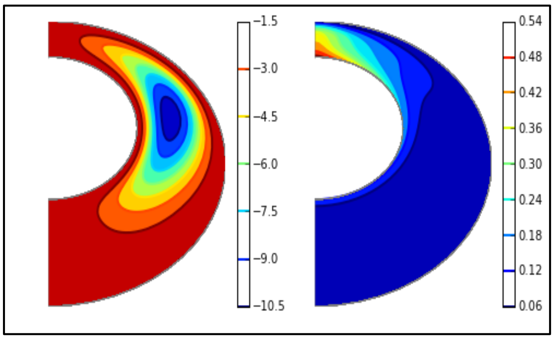




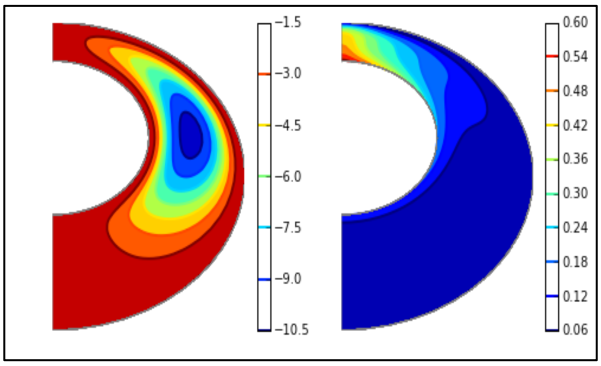
t = 5.10^{-1} t = 1

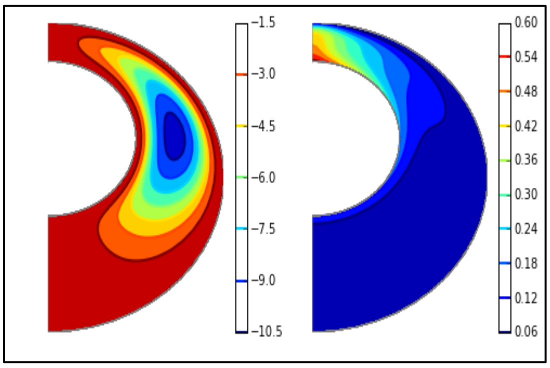
Figure 2: Isocurrents and isotherms for Ra = 10^5; e =-0.5; Ha=10; $\varphi = 0$





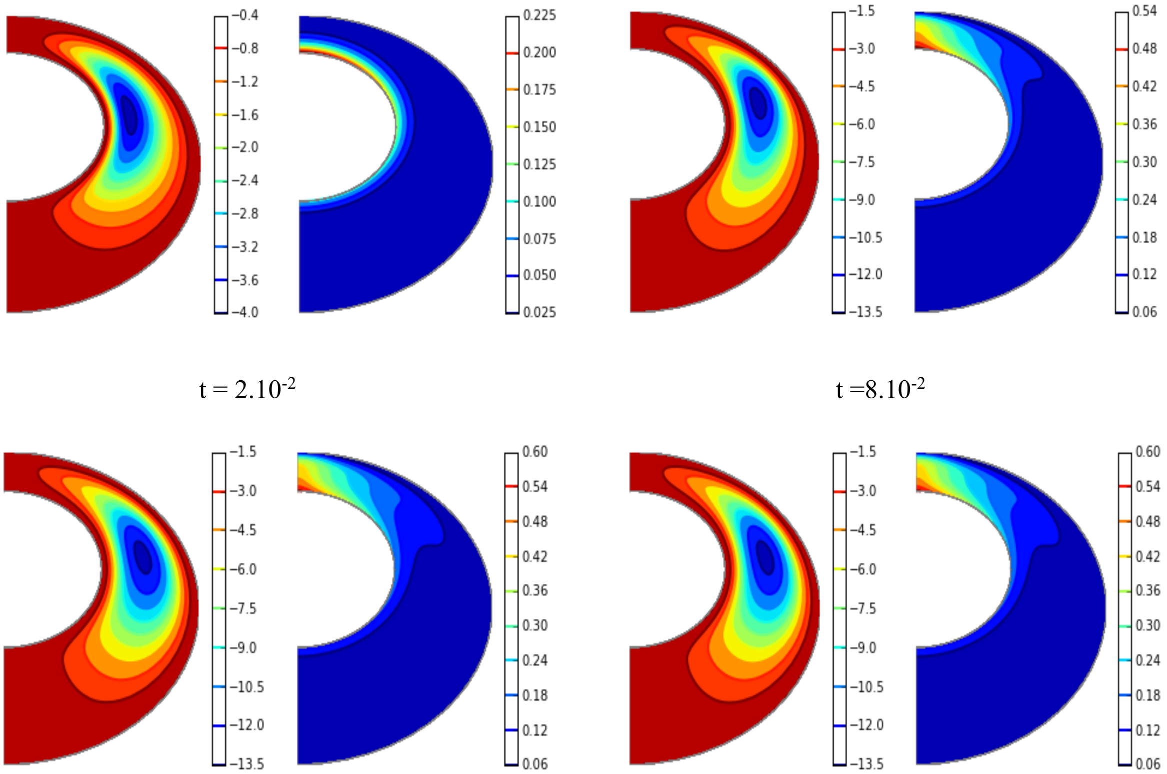
t = 2.10^{-2} t =8.10^{-2}





t = 5.10^{-1} t = 1

Figure 3: Isocurrents and isotherms for Ra = 10^5; e =-0.5; Ha=10; $\varphi = \pi/4$



t = 2.10^{-2} t =8.10^{-2}

t = 5.10^{-1} t = 1

Figure 4: Isocurrents and isotherms for Ra = 10^{5}; e =-0.5; Ha=10; $\varphi = \pi/2$

3.4.2 Minimum current function, Nusselt number and internal wall temperature

Through Figure 5, the evolution of the Nusselt number as a function of the dimensionless average temperature of the heated wall gives a small variation for different directions of the magnetic field. The Hartmann number being high, this means that the magnetic effect is predominant over the convection and viscosity forces. It therefore constrains the movements of the fluid and limits thermal convection. Regardless of the direction of the magnetic field, the convection of the fluid is reduced and the Nusselt number remains relatively constant. The dimensionless average temperature of the heated wall is higher if the magnetic field is horizontal, followed by the oblique field of angle φ=π/4 and finally the two fields of vertical direction then oblique φ=(3 π)/4. The more the magnetic field deviates from the horizontal direction, the more the thermal conductivity of the fluid increases and this facilitates the dissipation of heat through the wall. This results in a decrease in the average temperature of the spherical wall. A horizontal magnetic field gives a higher minimum current function. If the field direction is vertical, it becomes weaker than those with oblique directions. The inclination of the magnetic field can modify convection currents and therefore the heat transfer efficiency. The greater the inclination, the more convection is affected and the less efficient the heat transfer. This results in a lower minimum current function.

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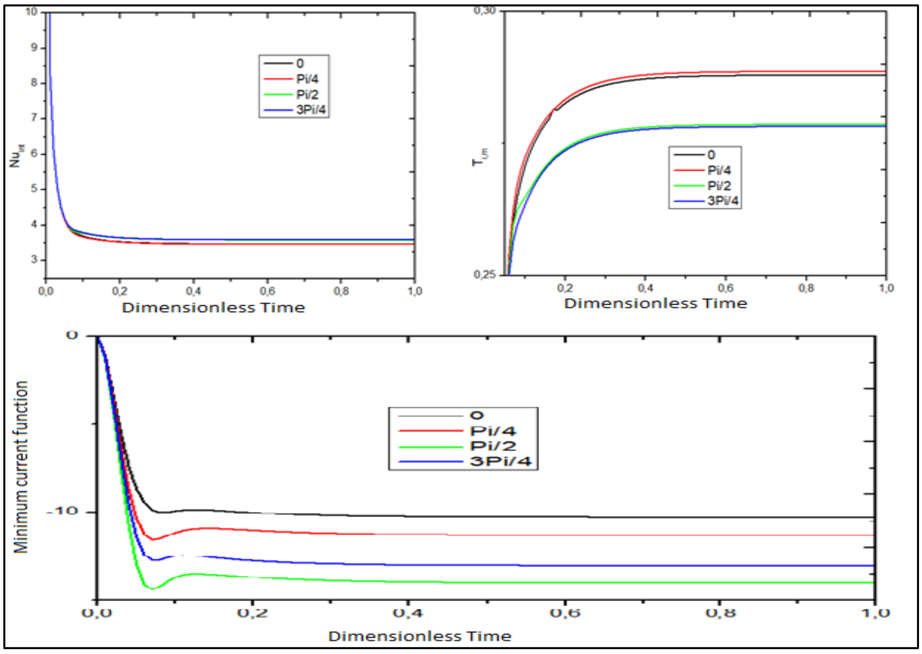

Figure 5: Influence of the magnetic field direction on various parameters

4. Conclusion

In this paper, we numerically studied the magneto-convection of a fluid confined between two vertically eccentric hemispheres. The hemispherical cavity studied is subjected to thermal and electrical boundary conditions in order to obtain the critical values of the parameters marking the onset of instability. The aim here is to highlight the effect of the magnetic field inclination on the magneto-convective transfer. To do this, a constant heat flux density is imposed on the inner hemispherical wall and a constant temperature on the outer hemisphere. The equations governing magneto-convection are projected into bispherical coordinates. Discretization by the finite difference method facilitated the development of a computer code in Fortran. The equations are solved using the ADI and SOR methods. Assumptions are made on the vorticity and flux function variables. At the end of the study, the results obtained are consistent and revealing:

The magnetic field tilt therefore modifies the convection currents and consequently affects the heat transfer efficiency. As it becomes increasingly steep, convection is more affected, making heat transfer less efficient. This obviously results in an increase in the Nusselt number, and the minimum current function becomes increasingly weaker.

Moreover, our results are in good agreement with the solutions available in the literature, such as [10], [20], etc.

Nomenclature

Latin	Grec
a, parameter of the torus pole (m) e, eccentricity g, gravitational intensity ($m.s^{-2}$) Coefficients g_1 and g_2 H and K: dimensionless metric coefficient B_0: magnetic field intensity ($N.A^{-1}.m^{-2}$) Ha: Hartmann number Nu_e: Nusselt number for the outer hemisphere Nu_i: Nusselt number for the inner hemisphere Oi and Oe: centers of the inner and outer hemispheres, respectively Pr: Prandtl number q: heat flux density ($W.m^{-2}$) Ri and Re: radius of the inner and outer hemispheres, respectively	α, thermal diffusivity, ($m^2.s^{-1}$) β, thermal expansion coefficient, (K^{-1}) σ, electrical conductivity, ($A.m.V^{-1}$) Δt, time step, (s) ΔT, temperature difference between the two hemispheres, (K) η and θ, bispherical coordinates, (m) λ, thermal conductivity, ($W.K^{-1}\cdot m^{-1}$) ν, kinematic viscosity, ($m^3\cdot s^{-1}$) Ψ, dimensionless flux function, Ψ′, dimensional flux function, ($m^3\cdot s^{-1}$) Ω, dimensionless vorticity, Ω', dimensional vorticity, ($m^3\cdot s^{-2}$)

Ra: Rayleigh number T: dimensionless time t': dimensional time (s) T: dimensionless temperature U and V: dimensionless components of velocity in the transformed planes x and y, Cartesian coordinates, (m)	

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