

Hydromagnetic Flow with Thermal Radiation

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1. Introduction

Magnetohydrodynamic (MHD) flows, which is the simplest plasma model, has been the subject of a great number of empirical and theoretical investigations in many industrial fields. Especially the MHD flows associating with heat transfer have received considerable attention so far, as their applications reside in many industrial fields such as electric propulsion for space exploration, crystal growth in liquids, cooling of nuclear reactors, electronic packages, micro electronic devices, etc.

The most common type of body force, which acts on fluid, is attributed to gravity so that the body force vector can be deduced from the gravitational acceleration. On the other hand, when an electrically conducting fluid is subjected to a magnetic field, the fluid motion induces an electric current such that the fluid velocity is reduced on account of interaction between the electric current and the fluid motion. Therefore, in case of free convection of an electrically conducting fluid in the presence of a magnetic field, there should be two body forces, i.e., a buoyancy force and a Lorentz force. They interact with each other, and in turn influence the transport phenomena of heat and mass.

Among various studies for MHD free flows, rather small amount of studies have been accomplished for the confined enclosures. Seki et al. (1979) studied the laminar natural convection of mercury subjected to a magnetic field parallel to gravity in a rectangular enclosure. Numerical results were obtained and compared to their experiment in the consideration of a partially heated vertical wall by a uniform heat generator. Rudraiah et al. (1995) performed a numerical simulation about natural convection in a two-dimensional cavity filled with an electrically conducting fluid in the presence of a magnetic field aligned to gravity. They selected the Grashof and Hartmann numbers as controlling parameters to examine the effect of a magnetic field on free convection and associated heat transfer. The three-dimensional free convective flow in a cubical enclosure in the presence of a transverse magnetic field was analysed by Kolsi et al. (2007) numerically.

For the free convection in an inclined enclosure under a magnetic field, the following representative works have been conducted. Bian et al. (1996) have studied the effect of a transverse magnetic field on buoyancy-driven convection in an inclined rectangular porous cavity, saturated with an electrically conducting fluid. Recently Wang et al. (2007) investigated numerically the natural convection in an inclined enclosure filled with porous media when a strong magnetic field was applied. They modelled the cubic enclosure, such that the direction of an applied magnetic field is varied in accordance with the inclination

angle. Differentially heated two side walls were kept to be vertical regardless of an inclination angle in their analysis.

Investigations considering the variation in the orientation of an external magnetic field applied were carried out too. The effect of direction of an external magnetic field on a low Prandtl number fluid in a cubical enclosure was numerically examined by Ozoe & Okada (1989). Hua & Walker (1995) examined the three-dimensional liquid metal MHD flow in rectangular ducts with thin conducting walls and an inclined transverse magnetic field against the principal axes. On the other hand, Bessaih et al. (1999) studied the buoyancy-induced flow of gallium in cavities simulating the apparatus for crystal growth. The combined effect on the flow structure of wall electrical conductivity and magnetic field orientation were numerically investigated in their work. Sivasankaran & Ho (2008) conducted the numerical analysis for natural convection of water near its density maximum in the presence of a magnetic field in a cavity with temperature dependent properties. They observed the effect of the direction of an external magnetic field on the flow field and accompanying heat transfer when varying it from 0 to $\pi/2$ radians.

Moreover many researchers have taken an interest in the effect of thermal radiation on the hydromagnetic flow and heat transfer problems, by reason of its great importance in diverse industrial fields. Radiation effect can be quite significant at high operating temperature. Many processes in engineering areas occur at high temperatures and the knowledge of radiation heat transfer becomes very important for the design of pertinent equipments. The effects of thermal radiation on hydromagnetic boundary layer flows were studied by Chamkha (2000), Seddeek (2002), Ghaly (2002) and Raptis et al. (2004). However they converted the complex radiation problem to the simpler conduction one accounting for the radiation conductivity by introducing the similarity transformation as a sort of the one-dimensional analysis. This analytical approach is not suitable for the assessment of the radiant heat exchange between surfaces of an enclosure operating under the high temperature environment, as the multi-dimensional analysis should be required in this case. Mahmud & Fraser (2002) examined analytically radiation effects on mixed convection through a vertical channel in the presence of a transverse magnetic field, but the underlying drawbacks are similar to those for studies aforementioned.

The aim of present chapter is to investigate in detail the effect of a magnetic field as well as thermal radiation on free convection associating with heat transfer in an enclosure filled with an electrically conducting fluid. Basically the full two-dimensional analysis is performed rather than the boundary layer type of analysis, even when considering the thermal radiation. It is motivated by a desire to find any effects of the controlling parameters on the thermally driven hydromagnetic flows found in many engineering applications. In this context this chapter can be classified into three subjects. In the first place the changes in the buoyant flow patterns and temperature distributions due to the tilting of the enclosure are examined, neglecting thermal radiation. Secondly the flow and thermal field variation is investigated in terms of the orientation of an external magnetic field. Finally the effect of combined radiation and a magnetic field on the convective flow and heat transfer characteristics of an electrically conducting fluid is analysed and discussed in detail.

2. Analysis model

For many electrically conducting fluids used in laboratories, the electrical conductivity is usually small. Subsequently the magnetic Reynolds number should be very small. Therefore it is reasonable to assume that the induced magnetic field by the motion of the electrically

conducting fluid is negligible compared to the external magnetic field applied. Based on this assumption the electromagnetic retarding force and the buoyancy force terms are appeared in the relevant momentum equations, respectively, such that the governing equations are not amenable to the boundary layer type of analysis. In this simulation the SIMPLER algorithm (Patankar, 1980) is involved to estimate the flow field, which is numerically stable and being widely used. The resultant solution of the governing equations is to be proposed in association with the finite-volume method (Chai et al., 1994), which is compatible with assessing the radiant heat exchange between enclosure walls. The effect of controlling parameters pertaining to fluid flow, heat transfer characteristics and radiation involvement is evaluated numerically.

2.1 Governing equations

A schematic of the two-dimensional rectangular enclosure with width L and height H is shown in Fig. 1. It is filled with the electrically conducting fluid that is viscous and incompressible. The left- and right-hand-side walls are kept at T_C and T_H , respectively. The ceiling and floor are assumed to be insulated for both conduction and radiation.

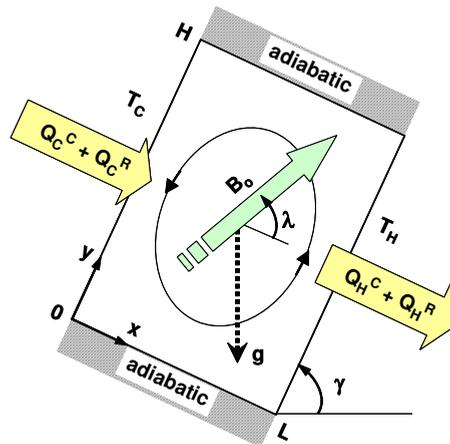


Fig. 1. Schematic diagram of the enclosure

The medium within the enclosure does not participate in radiation. Such nonparticipating medium example is intrinsically important in the analysis of nongray gas effects because there are wavelength regions where the medium is essentially transparent. All four walls of the enclosure are radiatively active surfaces, which are black and diffuse, so that the radiative interaction between walls is taken into account.

The fluid is permeated by the uniform magnetic field B_0 . The enclosure is tilted at an angle of γ with respect to the horizontal plane, and the orientation of an external magnetic field could vary from 0 to 2π radians corresponding to an angle of λ . In addition the induced electric current does not distort considerably the magnetic field applied. The fluid properties including the electrical conductivity are assumed to be constant except for the density, so that the Boussinesq approximation is used. Neglecting viscous and ohmic dissipations, the governing equations for mass, momentum and energy of the steady laminar flow are as follows.

Continuity

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (1)$$

X-momentum

$$\frac{\partial}{\partial x}(u^2) + \frac{\partial}{\partial y}(uv) = -\frac{1}{\rho} \frac{\partial p}{\partial x} + v \nabla^2 u - g\beta(T - T_o) \cos \gamma + \frac{\sigma B_o^2}{\rho} (-u \sin^2 \lambda + v \cos \lambda \sin \lambda) \quad (2)$$

Y-momentum

$$\frac{\partial}{\partial x}(uv) + \frac{\partial}{\partial y}(v^2) = -\frac{1}{\rho} \frac{\partial p}{\partial y} + v \nabla^2 v + g\beta(T - T_o) \sin \gamma + \frac{\sigma B_o^2}{\rho} (u \cos \lambda \sin \lambda - v \cos^2 \lambda) \quad (3)$$

Energy

$$\frac{\partial}{\partial x}(uT) + \frac{\partial}{\partial y}(vT) = \alpha \nabla^2 T \quad (4)$$

In the above equations, u and v are the velocity component in the x and y directions. The density, pressure and temperature are denoted by ρ , p and T , respectively. The relevant fluid properties are kinematic viscosity ν , thermal diffusivity α , electrical conductivity σ and volumetric expansion coefficient β . The governing equations are nondimensionalised using the following variables:

$$x^* = x/L, \quad y^* = y/L, \quad u^* = u/u_o, \quad v^* = v/u_o \quad (5)$$

$$p^* = \frac{p}{\rho_o u_o^2}, \quad T^* = \frac{T - T_o}{T_H - T_c} \quad (6)$$

$$\text{Pr} = \nu/\alpha, \quad \text{Ra} = \frac{g\beta\Delta T L^3}{\nu\alpha}, \quad \text{Gr} = \text{Ra}/\text{Pr}, \quad \text{Ha} = B_o L \sqrt{\frac{\sigma}{\mu}} \quad (7)$$

$$\delta = \frac{T_H - T_c}{T_o}, \quad \text{Pl} = \frac{k/L}{4\bar{\sigma} T_o^3}, \quad q^{R*} = \frac{q^R}{\bar{\sigma} T_o^4} \quad (8)$$

The reference velocity is defined as $u_o = \alpha/L$. The overheat ratio is expressed by δ , while the reference temperature is defined as the arithmetic mean of the two isothermal wall temperatures, i.e., $T_o = (T_H + T_c)/2$. The Prandtl, Rayleigh, Grashof, Hartmann and Planck numbers are represented by Pr , Ra , Gr , Ha and Pl , respectively, where μ and k are dynamic viscosity and thermal conductivity. Radiative heat flux q^R is nondimensionalised by the reference emissive power, i.e., $\bar{\sigma} T_o^4$, in which $\bar{\sigma}$ is Stefan-Boltzmann constant. Based on the presumptions above, the dimensionless governing equations can be shown as follows.

Continuity

$$\frac{\partial u^*}{\partial x^*} + \frac{\partial v^*}{\partial y^*} = 0 \quad (9)$$

X-momentum

$$\frac{\partial}{\partial x^*}(u^* v^*) + \frac{\partial}{\partial y^*}(u^* v^*) = -\frac{\partial p^*}{\partial x^*} + \text{Pr} \nabla^{*2} u^* - \text{Gr} \text{Pr}^2 T^* \cos \gamma + \text{Pr} \text{Ha}^2 (-u^* \sin^2 \lambda + v^* \cos \lambda \sin \lambda) \quad (10)$$

Y-momentum

$$\frac{\partial}{\partial x^*}(u^* v^*) + \frac{\partial}{\partial y^*}(v^{*2}) = -\frac{\partial p^*}{\partial y^*} + \text{Pr} \nabla^{*2} v^* + \text{Gr} \text{Pr}^2 T^* \sin \gamma + \text{Pr} \text{Ha}^2 (u^* \cos \lambda \sin \lambda - v^* \cos^2 \lambda) \quad (11)$$

Energy

$$\frac{\partial}{\partial x^*}(u^* T^*) + \frac{\partial}{\partial y^*}(v^* T^*) = \nabla^{*2} T^* \quad (12)$$

2.2 Dimensionless boundary conditions

The boundary conditions for two isothermal walls are as follows:

$$u^* = v^* = 0, T^* = -0.5 \text{ at } x^* = 0 \quad (13)$$

$$u^* = v^* = 0, T^* = 0.5 \text{ at } x^* = 1 \quad (14)$$

Non-slip conditions of the velocities are assigned on the ceiling and floor. The thermal boundary condition at adiabatic ceiling and floor is found from the following energy balancing equation, in which the net radiation into the wall surface is balanced by conductive heat loss from the wall:

$$-\frac{\partial T^*}{\partial y^*} \Big|_w + \frac{q_w^R}{4 \text{Pl} \delta} = 0 \quad (15)$$

2.3 Heat transfer rates

To estimate the heat transfer rates at two isothermal walls, various types of average Nusselt numbers are defined as follows:

$$\overline{\text{Nu}}_w^C = \frac{1}{A} \int_0^A \left[-\frac{\partial T^*}{\partial x^*} \right]_w dy \quad (16)$$

$$\overline{\text{Nu}}_w^R = \frac{1}{4 \text{Pl} \delta} \frac{1}{A} \int_0^A \text{sign}(\hat{n}_w) \cdot q_w^R dy \quad (17)$$

$$\overline{\text{Nu}}_w^T = \overline{\text{Nu}}_w^C + \overline{\text{Nu}}_w^R \quad (18)$$

From the above equations, A means the aspect ratio, i.e., $A = H/L$. The conductive and radiative average Nusselt numbers at the walls are represented by $\overline{\text{Nu}}_w^C$ and $\overline{\text{Nu}}_w^R$, respectively. Their sum, $\overline{\text{Nu}}_w^T$ is the total average Nusselt number, which denotes the total amount of heat transfer at the wall. Since the steady state is assumed in this study, the total average Nusselt numbers at both hot and cold walls are same.

3. Numerical analysis

A numerical analysis of thermo-fluid dynamics characteristics is conducted by adopting the SIMPLER algorithm developed by Patankar (1980). While the convection term is discretised using the QUICK finite-difference scheme (Thakur & Shyy, 1993), the central difference method is chosen for the diffusion term. In order to compute the radiative heat fluxes on enclosure walls, the finite-volume method (FVM) for radiation heat transfer is implemented here as proposed by Chai et al. (1994). After some preliminary calculations for checking convergence and accuracy, the spatial domain is discretised into 51×51 non-uniform control volumes in the x and y directions. In the case of radiation, 48 control angles are employed to estimate the radiative wall heat fluxes accordingly.

Computations are proceeded by the following procedures. To begin with, the radiative wall heat fluxes are determined by FVM. The velocity field is estimated from the momentum equation. After the updated temperature is estimated from the energy equation based on the interior point temperature at the previous iteration, the wall conductive heat fluxes are estimated. Then, these values of the wall conductive heat flux and the radiative wall heat flux are used to update the non-prescribed wall surface temperatures by solving the energy balance equation (15). In computation, to reduce the error in the wall conductive heat flux, the grid system should be clustered near the walls. Since the calculation of radiative heat fluxes is not necessarily required at every iteration to produce a reliable steady-state result, the radiative heat flux is updated at every tenth iteration. However, the wall surface temperature is recalculated and changed at each iteration with an estimated wall conductive heat flux.

Finally, the convergence criteria for main variables are checked if the steady state is reached. Computations are terminated when the difference in total average Nusselt numbers for the hot and cold walls is within less than 10^{-3} tolerance to meet the overall energy balance in the enclosure.

$$\left| \overline{Nu}_H - \overline{Nu}_C \right| \leq 10^{-3} \quad (19)$$

4. Results and discussion

A numerical investigation is presented for free convection in a two-dimensional enclosure filled with an electrically conducting fluid in the presence of an external magnetic field. The enclosure is such that the two opposing side walls are differentially heated with a temperature difference specified, while the top and bottom walls are insulated. Those four walls are radiatively active surfaces, and the enclosure is tilted as well as the orientation of an external magnetic field can be arbitrary. As a whole computations are carried out for the Grashof numbers ranging from 1×10^4 to 2×10^6 , and Hartmann numbers from 0 to 100. The assumption of two-dimensional laminar flow is valid for above values of the Grashof numbers (Larson & Viskanta, 1976).

It is difficult to study the influence of all parameters involved in the present problem on the flow and thermal field. Therefore a selected set of parameters is accounted for this numerical investigation. The aspect ratio, $A = H/L$, of the enclosure is set to be of 1, and the Prandtl number of 0.733 is utilised. The overheat ratio is taken to be $\delta = 2/3$, i.e., $T_H = 2 T_C$. The constant fluid property and Boussinesq approximations are reasonable for above values (Fusegi & Farouk, 1989). The Planck number is assigned to be 0.02.

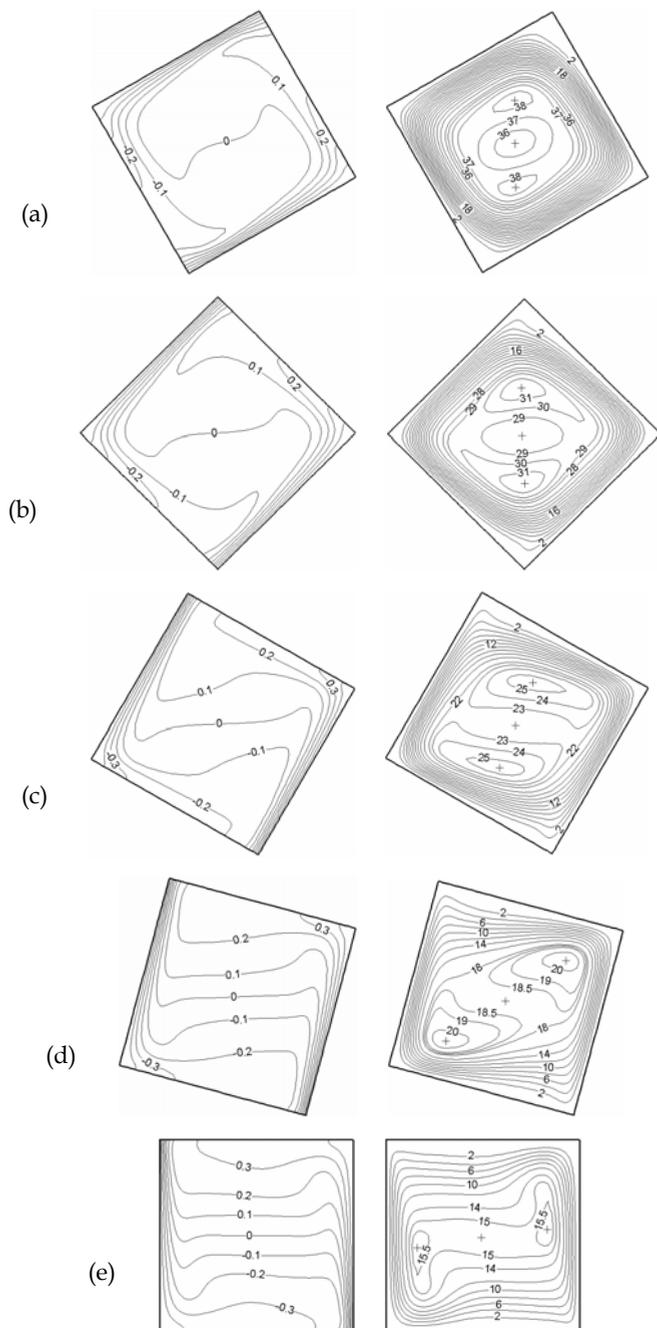


Fig. 2. Isotherm and streamline contours for $Gr = 10^6$ and $Ha = 0$: (a) $\gamma = \pi/6$, (b) $\gamma = \pi/4$, (c) $\gamma = \pi/3$, (d) $\gamma = 5\pi/12$ and (e) $\gamma = \pi/2$ radians

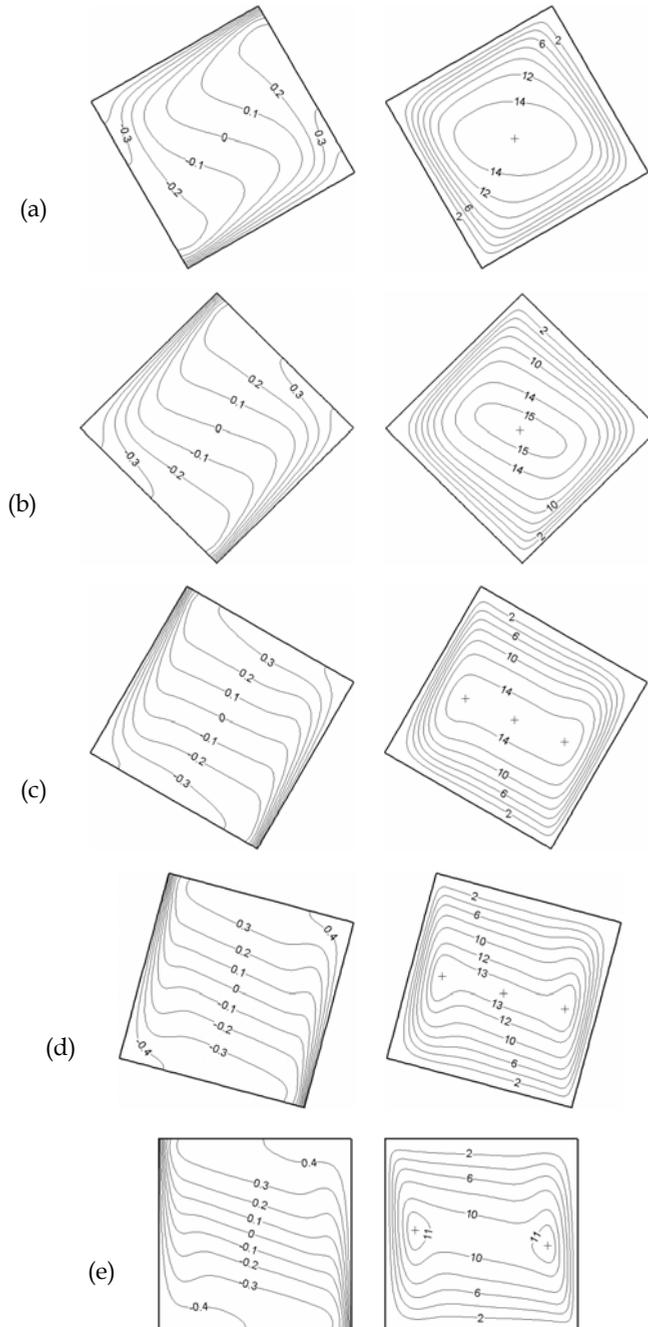


Fig. 3. Isotherm and streamline contours for $Gr = 10^6$ and $Ha = 50$: (a) $\gamma = \pi/6$, (b) $\gamma = \pi/4$, (c) $\gamma = \pi/3$, (d) $\gamma = 5\pi/12$ and (e) $\gamma = \pi/2$ radians

Isotherm and streamline plots will be reported for different values of controlling parameters. The contour lines of isotherm plots correspond to equally-spaced values of the dimensionless temperature T^* , i.e., $\Delta T^* = 0.1$, in the range between -0.5 and +0.5. On the other hand the dimensionless stream function is obtained from the velocity field solution by integrating the integral $\Psi^* = \int_0^1 u^* dy^*$ along constant x^* lines, setting $\Psi^* = 0$ at $x^* = y^* = 0$.

The contour lines of the streamline plots are correspondent to equally-spaced values of the dimensionless stream function, unless otherwise specified.

4.1 Influence of the tilting of an enclosure without radiation

A numerical investigation is presented for natural convection of an electrically conducting fluid in a tilted square cavity in the presence of a vertical magnetic field aligned to the gravity, i.e., $\lambda = -\gamma$.

In the present study, the Grashof number is fixed as $Gr = 10^6$. Computations are carried out for tilted angles ranging from 0 to $\pi/2$ radians, and the thermal radiation is neglected.

Figure 2 shows the isotherm and streamline contours for natural convection in inclined cavities in the absence of a magnetic field. The multi-cellular inner core consists of a central roll (designated by "+" in the figures) sandwiched between two rolls. As the tilting angle decreases, the fluid motion becomes progressively intensive. The temperature is stratified at the core region in case of $\gamma = \pi/2$ rad. When the tilting angle decreases, this trend is maintained until $\gamma = \pi/4$ rad. The stratification of the temperature field in the interior begins to diminish as the inclination angle reaches $\pi/6$ rad due to the increasing buoyant action.

The results depicted in Fig. 3 demonstrate the influence of the magnetic field on the fluid flow and the temperature distributions along with the tilting angle. For relatively strong Hartmann number ($Ha = 50$), the temperature stratification in the core tends to diminish, and the thermal boundary layers at the two side walls disappear, together with the decrease in inclination angle. Also, the streamlines are elongated, and the core region becomes broadly stagnated. Furthermore, the axes of the streamlines are changed, which is due to the retarding effect of the Lorentz force. In addition, the flow strength displays maximum at $\gamma = \pi/4$ rad in this case, then, it decreases when γ reaches $\pi/6$ rad. This phenomenon is different from the previous result for pure free convection; hence, a considerable interaction between the buoyant and the magnetic forces is evidently caused by the tilting, as the magnitude of the Lorentz force in the x and y directions is subjected to the inclination angle.

4.2 Effect of the orientation of a magnetic field without radiation

Hydromagnetic flow in a horizontal enclosure ($\gamma = \pi/2$ rad) under a uniform magnetic field is studied. The changes in the flow and thermal field based on the orientation of an external magnetic field, which varies from 0 to 2π radians, are investigated in the absence of the thermal radiation. Assuming constant buoyant action, Gr is fixed as 10^6 .

The source terms caused by the Lorentz force in Eqs. (10) & (11) are such that they are function of $\sin^2\lambda$ and $\cos\lambda\sin\lambda$ as well as $\cos^2\lambda$, which have the common period of π radians. Thus the numerical simulation is conducted with directional variation of a magnetic field applied from $\lambda = 0$ to π rad on account of the phase difference of π radians.

In Fig. 4, thermo-fluidic behaviour in an enclosure is displayed as to the slanted angle of a magnetic field when $Ha = 50$. The flow intensity varies in accordance with the change of λ and it becomes strongest as $\lambda = 3\pi/4$ rad. This phenomenon can be explained from the flow

retardation induced by direct interaction between the magnetic field and the velocity component perpendicular to the direction of the magnetic field. As for streamlines, the orientation of a magnetic field affects the elongation of streamlines. A uni-cellular inner core is formed along with a transverse magnetic field. Following the change in λ , the inner core gets a multi-cellular structure accompanying the elongation of streamlines at the central region. In terms of the thermal field, the tilting of isotherms is most severe with a vertical magnetic field.

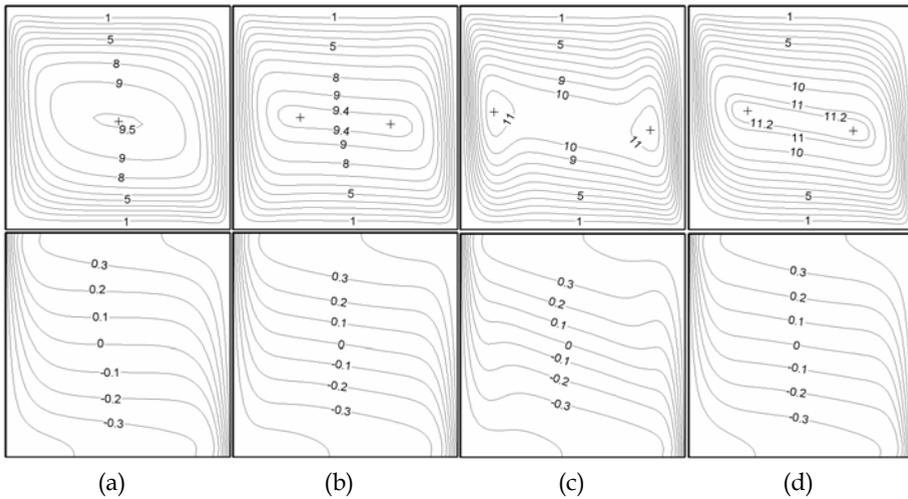


Fig. 4. Streamlines and isotherms for $Gr = 10^6$ and $Ha = 50$: (a) $\lambda = 0, \pi$ and 2π ; (b) $\lambda = \pi/4$ and $5\pi/4$; (c) $\lambda = \pi/2$ and $3\pi/2$; (d) $\lambda = 3\pi/4$ and $7\pi/4$ radians

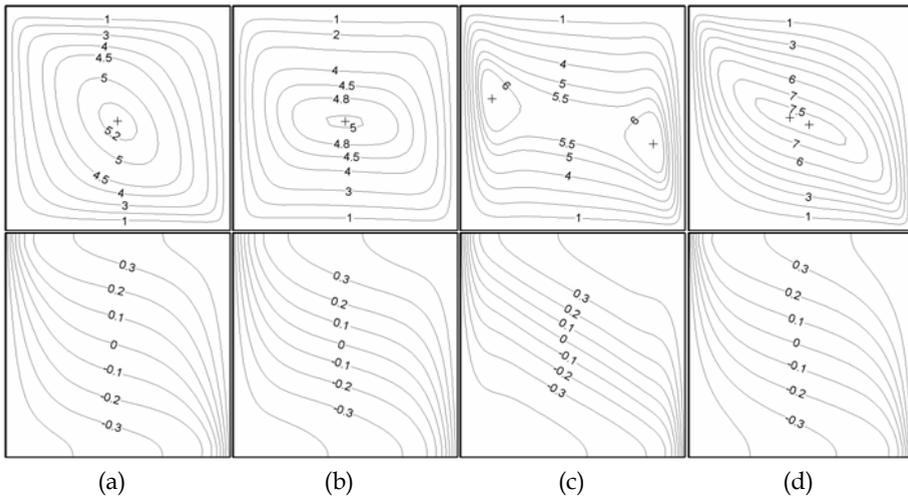


Fig. 5. Streamlines and isotherms for $Gr = 10^6$ and $Ha = 100$: (a) $\lambda = 0, \pi$ and 2π ; (b) $\lambda = \pi/4$ and $5\pi/4$; (c) $\lambda = \pi/2$ and $3\pi/2$; (d) $\lambda = 3\pi/4$ and $7\pi/4$ radians

The changes in flow and thermal fields together with λ are illustrated in Fig. 5, in the case of a strong magnetic field, i.e., $Ha = 100$. The tendency in the variation of flow and thermal fields influenced by λ , seems to be similar to that for the prior case. A multi-cellular core structure, however, start to appear at the later stage comparing with the case of $Ha = 50$; in contrast a uni-cellular core structure is recovered at the earlier stage. It is inferred that stronger magnetic field plays a role to suppress the transition of the inner core structure as λ varies 0 to $\pi/2$ radians. Inclination of isotherms is obvious than Fig. 4. With a vertically permeated magnetic field, the inclination of isotherms is most conspicuous.

4.3 Effect of combined radiation and a magnetic field

Computation is carried out for free convection of an electrically conducting fluid in a square enclosure encompassed with radiatively active walls in the presence of a vertically assigned magnetic field parallel to the gravity. In that case, γ is fixed as $\pi/2$ rad so that λ is $-\pi/2$ rad. Radiation-affected temperature and buoyant flow fields in a square enclosure are demonstrated with $Gr = 2 \times 10^6$, in the absence of an external magnetic field, i.e., $Ha = 0$, as presented in Fig. 6 (a). The radiative interaction between the hot and cold walls is significant so that the colder region is extended further into the mid-region. The temperature gradients at the adiabatic walls are steeper owing to the increased interaction by means of the surface radiation. The flow field displays a multi-cellular structure, and the inner core consists of two convective rolls in upper and lower halves, respectively.

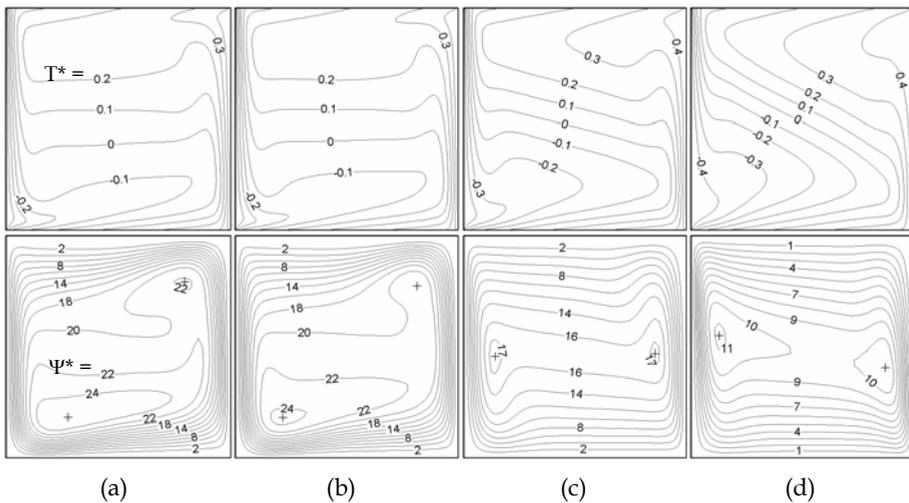


Fig. 6. Isotherm and streamline contours with $Gr = 2 \times 10^6$: (a) $Ha = 0$, (b) $Ha = 10$, (c) $Ha = 50$ and (d) $Ha = 100$

It is seen that for a weak magnetic field ($Ha = 10$), as shown in Fig. 6 (b), the isotherms and streamlines are almost similar to those in the absence of an external magnetic field, i.e., $Ha = 0$. The flow field becomes less intensive a little bit than that corresponding to the streamline plot in Fig. 6 (a). As a relatively strong magnetic field is applied, i.e., $Ha = 50$, the thermal and flow fields are considerably changed as depicted in Fig. 6 (c). The streamlines are elongated laterally and the axis of the streamline is slanted. The former convective roll at

the lower left part of the enclosure moves upward. On the contrary the convective roll which was at the upper right region moves downward as to increase in the strength of a magnetic field applied. In the case of the thermal field, severe temperature gradients caused by the surface radiation are maintained at adiabatic top and bottom walls. In mid-region the tilting of isotherms coincides with steeper temperature gradient observed by in-between distance of isotherms getting narrower. These tendencies are preserved until Ha reaches 100, as illustrated in Fig. 6 (d). Besides such typical influence of a magnetic field as the tilting of isotherms and streamlines, appears to be emphasised with the suppression of convection in an enclosure.

Gr	Radiation	Ha	Left cold wall		Right hot wall		\overline{Nu}^T
			\overline{Nu}^C	\overline{Nu}^R	\overline{Nu}^C	\overline{Nu}^R	
2×10^4	Without	0	2.523	0.000	2.523	0.000	2.523
		10	2.220	0.000	2.220	0.000	2.220
		50	1.118	0.000	1.118	0.000	1.118
		100	1.116	0.000	1.116	0.000	1.116
	With	0	4.049	36.733	2.105	38.678	40.783
		10	3.754	36.759	1.874	38.641	40.513
		50	3.021	36.841	1.368	38.494	39.862
		100	2.997	36.846	1.357	38.487	39.843
2×10^5	Without	0	5.090	0.000	5.090	0.000	5.090
		10	4.983	0.000	4.983	0.000	4.983
		50	2.997	0.000	2.997	0.000	2.997
		100	1.454	0.000	1.454	0.000	1.454
	With	0	6.138	36.486	3.639	38.987	42.624
		10	5.986	36.513	3.530	38.970	42.499
		50	4.083	36.704	2.068	38.721	40.787
		100	3.174	36.808	1.446	38.537	39.982
2×10^6	Without	0	9.904	0.000	9.904	0.000	9.904
		10	9.863	0.000	9.863	0.000	9.863
		50	8.891	0.000	8.891	0.000	8.891
		100	6.640	0.000	6.640	0.000	6.640
	With	0	10.413	36.047	6.946	39.514	46.460
		10	10.339	36.073	6.914	39.499	46.412
		50	9.025	36.313	6.050	39.289	45.338
		100	6.699	36.531	4.178	39.054	43.230

Table 1. Nusselt numbers estimated

The rate of heat transfer across the enclosure is attained by evaluating the conductive, radiative, and total average Nusselt numbers, i.e., \overline{Nu}^C , \overline{Nu}^R , and \overline{Nu}^T , respectively, at the hot and cold walls, and tabulated in Table 1 for various combinations of parameters. From this table it can be demonstrated that the introduction of a magnetic field suppresses the convection in the enclosure. With the thermal radiation getting involved in, the radiative contribution to the combined heat transfer is predominant at both hot and cold walls. In addition the convective contribution to the combined heat transfer at the cold wall is always larger than that at the hot wall disregarding the Grashof number and the radiation effect.

5. Conclusions

Free convection in a two-dimensional enclosure filled with an electrically conducting fluid in the presence of an external magnetic field was investigated numerically. The effects of the controlling parameters on the thermally driven hydromagnetic flows have been scrutinised. In the first place the changes in the buoyant flow patterns and temperature distributions due to the tilting of the enclosure were examined neglecting thermal radiation. In general terms, the effect of the tilting angle on the flow patterns and associated heat transfer was found to be considerable. The variation of flow strength was affected by the orientation of the cavity with imposition of the magnetic field because the effective electromagnetic retarding force in each flow direction was subjected closely to the inclination angle. The flow structure and the temperature field were enormously affected by the strength of the magnetic field, regardless of the tilting angle.

Secondly the flow and thermal field variation was investigated in terms of the orientation of an external magnetic field. The flow intensity and structure varied in accordance with the change of the direction of an external magnetic field. The flow retardation appeared by direct interaction between the magnetic field and the velocity component perpendicular to the direction of the magnetic field. In terms of the thermal field, the tilting of isotherms was observed.

Finally the effects of combined radiation and a magnetic field on the convective flow and heat transfer characteristics of an electrically conducting fluid were investigated. It was concluded that the radiation was the dominant mode of heat transfer and surpassed convective heat transfer so that it played an important role in developing the hydromagnetic free convective flow in a differentially heated enclosure.

As a consequence, all the numerical analyses so far have been subjected to the rectangular enclosure. Hence the future studies are supposed to be related to the general geometries containing an electrically conducting fluid with the permeation of an external magnetic field as well as the participation in radiation.

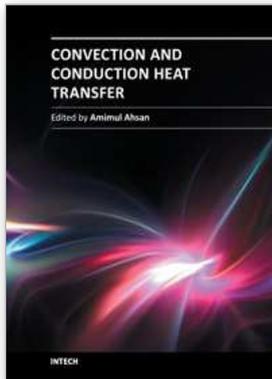
6. Acknowledgment

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The convection and conduction heat transfer, thermal conductivity, and phase transformations are significant issues in a design of wide range of industrial processes and devices. This book includes 18 advanced and revised contributions, and it covers mainly (1) heat convection, (2) heat conduction, and (3) heat transfer analysis. The first section introduces mixed convection studies on inclined channels, double diffusive coupling, and on lid driven trapezoidal cavity, forced natural convection through a roof, convection on non-isothermal jet oscillations, unsteady pulsed flow, and hydromagnetic flow with thermal radiation. The second section covers heat conduction in capillary porous bodies and in structures made of functionally graded materials, integral transforms for heat conduction problems, non-linear radiative-conductive heat transfer, thermal conductivity of gas diffusion layers and multi-component natural systems, thermal behavior of the ink, primer and paint, heating in biothermal systems, and RBF finite difference approach in heat conduction. The third section includes heat transfer analysis of reinforced concrete beam, modeling of heat transfer and phase transformations, boundary conditions-surface heat flux and temperature, simulation of phase change materials, and finite element methods of factorial design. The advanced idea and information described here will be fruitful for the readers to find a sustainable solution in an industrialized society.

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