Journal of Applied Fluid Mechanics, Vol. 8, No. 3, pp. 429- 438, 2015.
Available online at www.jafmonline.net, ISSN 1735-3572, EISSN 1735-3645.
DOI: 10.18869/acadpub.jafm.67.222.22825

The Radiation Effect on the Thermo-Magnetic Convection in Participating Paramagnetic Medium under Microgravity Condition

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(Received March 12, 2014; accepted July 04, 2014)

ABSTRACT

The radiation effect on the thermo-magnetic convection which occurs in participating paramagnetic medium under microgravity (g = 0) condition is numerically investigated. Different from the electrically conducting fluid, the paramagnetic fluid is driven by Kelvin force which is proportional to the product of magnetic susceptibility and the gradient of the square of the magnetic induction and is introduced into the source term of the Navier-Stokes equation. In order to realize the fluid flow, an external magnetic field with uniform or non-uniform magnetic gradient is imposed. Further, the thermo-magnetic convection is carried out in high temperature field, in which the magnetic susceptibility varies greatly with absolute temperature according to Curie's law, and the radiation field is also modified by the absorbing-emitting paramagnetic medium. In the present study, the effects of magnetic Rayleigh number and optical thickness are investigated. The results show that radiative heat transfer plays a significant role in thermo-magnetic convection.

Keywords: Paramagnetic fluid; Thermo-magnetic convection; Kelvin force; Radiative transfer; Microgravity.

NOMENCLATURE

b , B	magnetic induction
g	gravitational acceleration, m s^{-2}
k	thermal conductivity, W m^{-1} K^{-1}
I	intensity
L	reference length, m
$\hat{n}$	unit inward normal vector at the boundary location
Nu_c	convective Nusselt number
Nu_r	radiative Nusselt number
Nu_T	total Nusselt number
p	pressure
Pl	Plank number
Pr	Prandtl number
$\vec{q}_c$	convective heat flux
$\vec{q}_r$	radiative heat flux
Ra	Rayleigh number
t	time
T	temperature
$\vec{v}$	velocity
x , y	Cartesian coordinates
α_0	thermal diffusivity
β	extinction coefficient, m^{-1}
β'	thermal expansion coefficient, K^{-1}
γ	strength of the magnetic force
ε	wall emissivity
Θ	dimensionless temperature for radiation computation
κ	absorption coefficient, m^{-1}
μ , η	components of the direction vector
μ_m	magnetic permeability, N A^{-2}
ν_0	kinematic viscosity, m^2 s^{-1}
ρ	density, kg m^{-3}
σ	Stefan-Boltzmann constant, 5.67×10^{-8} W m^{-2} K^{-4}
τ	optical thickness $\tau = \beta L$
χ_m	magnetic susceptibility, m^3 kg^{-1}
Ω	unit direction vector of radiation propagation

Superscript

+	original variable

1. INTRODUCTION

Different from the electrically conducting fluid, the paramagnetic fluid will experience a magnetic force, which is also called the Kelvin force, if it is placed in a magnetic field. The Kelvin force, in the form $\vec{f} = \chi / \mu_0 \nabla b^2$, is proportional to the product of the magnetic susceptibility and the gradient of the square of the magnetic induction. In addition, the magnetic susceptibility varies with absolute temperature according to Curie's law. So paramagnetic fluid motion could also occur under microgravity condition.

The magnetic convection of gadolinium nitrate in paramagnetic fluid form was first verified experimentally by Braithwaite *et al.* (1991). The results showed that a magnetic field could enhance or suppress natural convection. The Kelvin force acts at the molecular level, so it could be used as a way of local control for the fluid convection. With the development of material science, superconducting magnets could provide more and more magnetic induction and the control of thermo-magnetic convection for commercial purposes will be possible. In the last decade, the thermo-magnetic convection phenomenon has received more and more interest by many researchers and used to control the quality of crystallization for materials (Ganapathysubramanian *et al.* 2005) and protein crystal (Baird *et al*. 2013; Sazaki 2009; Wakayama 2003), assist breathing (Wakayama *et al*. 2000), control thermal convection without any mechanical driving parts (Sadat *et al*. 2011; Uetake *et al*. 2000), support combustion in microgravity condition (Wakayama 1999), and many other applications.

In processes involving high temperature, such as the solidification of crystal, the melt is sometimes a kind of semitransparent medium that absorbs and emits energy, or diffuses energy if there are impurities in it. Therefore, the radiation effect couldn't be neglected in such processes. During the last decade, the effect of thermal radiation on thermo-magnetic convection has been investigated by many researchers.

Ghaly *et al.* (2002a, b), Raptis *et al.* (2004) and Mahmoud (2009) examined the radiation effect on the boundary layer of steady magnetohydrodynamics (MHD) free-convection flow by using the Rosseland approximation. Ghosh *et al.* (2015) further considered transient MHD radiating flow with the presence of mass transfer or chemical reaction. Numerical results showed that radiation has significant influences on the velocity, temperature, and other quantities of physical interest (Wang *et al.* 2014). Mahapatra *et al.* (2013) investigated thermal radiation acting on an unsteady two-dimensional laminar magnetic natural convection flow in an inclined enclosure. In their study, decreasing the values of radiation parameters while keeping other parameters fixed led to a decrease in the average Nusselt number. Mahmud *et al.* (2002) studied the effects of radiation heat transfer on mixed convection through a vertical channel in the presence of a transverse magnetic field with the two-flux approximation or the Schuster-Schwarzschild approximation for the RTE. It was found that radiation could suppress the velocity profile around the centre line of the channel and introduce nonlinearity in temperature profiles. The Rosseland and two-flux approximations generally offer low accuracy and are only suitable for optically thick and thin media respectively. Moreover, previous studies mainly dealt with the radiation effect on the boundary layer flows.

Han (2009) became the first to solve the RTE by employing the finite volume method (FVM) to investigate the effect of radiation on the natural convection of an electrically conducting and radiating fluid contained in the square in the presence of an external magnetic field aligned with gravity. Zhang et al. (2013a, b) continued the research by considering more complicated situations, including the scattering effects of the participating fluid and the reflection of surrounding walls, by using DOM for the RTE. They concluded that radiation plays an important role in the fluid flow and heat transfer in thermo-magnetic convection, in addition, Hall effects on participating MHD could be found. Luo et al. (2014) analyzed the thermal radiation effects on magnetohydrodynamics free convection by employing Chebyshev collocation spectral method. Jena et al. (2014) found that thermal radiation could suppress convection as it reduces the local temperature difference. For an optically thin medium, the radiation effect on a thermal field is limited in the vicinity of the adiabatic walls. On the other hand, for an optically thick medium, thermal radiation affects the flow structure and thermal field in the entire domain. Jena et al. (2015) further studied the surface radiation effect on MHD convection which occurred in the 3D rectangular cavity. They found that secondary cells at higher Rayleigh numbers disappear in the presence of surface radiation.

All the researchers mentioned above examined the effects of thermal radiation on MHD of electrically conducting fluid in a gravitational field. The main goal of this paper is to show how radiation affects the thermo-magnetic convection and heat transfer rates of semitransparent non-conducting paramagnetic fluid under micro-gravity condition, in which thermo-magnetic convection is a direct consequence of temperature difference within fluid that has been placed in a magnetic field. Besides, our research is an exploratory work for the experiments in space, for example, to obtain more perfect crystals under microgravity condition. In this paper, the effects of the magnetic Rayleigh number γRa and optical thickness τ on the distributions of flow pattern and isotherms are presented and analyzed.

2. PHYSICAL MODEL AND MATHEMATICAL FORMULATION

2.1 Description of the Problem

In our simulation, the thermo-magnetic convection occurs in a square cavity, which is shown in Fig. 1. The fluid is Newtonian, incompressible, isotropic, and homogeneous. It is also assumed to be a semitransparent gray medium that absorbs and emits energy. The density depends weakly on temperature following the Boussinesq approximation. The flow is laminar. The temperatures on the left and right walls are constant, while the adiabatic boundary condition is used on the top and bottom walls. The fluid flow is placed in an external magnetic field with uniform or non-uniform magnetic gradient in the y direction. In microgravity, the magnetic force takes the place of the buoyancy force, which is generated by gravity, and becomes the driving force.

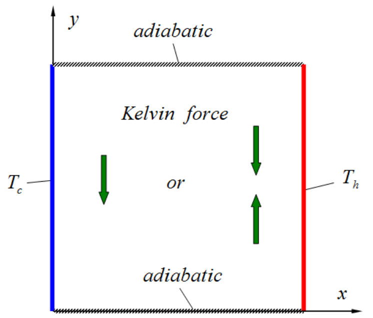

Fig. 1. Physical model

2.2 Governing Equations

We define $\Delta T = T_h^+ - T_c^+$ and $T_{ref} = \left(T_h^+ + T_c^+\right)/2$, where T_h^+ and T_c^+ are the high and low temperatures. We also introduce the dimensionless variables as following: $\vec{v} \to \dfrac{\vec{v}^+}{\alpha_0/L}$, $\vec{g} \to \dfrac{\vec{g}^+}{g_0}$,

$$t \to \frac{t^+}{L^2/\alpha_0},\quad T \to \frac{T^+ - T_{ref}}{\Delta T},\quad \Theta \to \frac{T^+}{T_{ref}} = \frac{\Delta T}{T_{ref}}T + 1,$$

$$p \to \frac{p^+}{\rho \nu_0^2},\quad I \to \frac{\pi I^+}{\sigma T_{ref}^4},\quad \tau \to \beta L,\quad \vec{q}_r \to \frac{\vec{q}_r^{\,+}}{k\Delta T/L},$$

$$b \to \frac{B}{B_0},\quad x \to \frac{x^+}{L},\quad y \to \frac{y^+}{L}.$$

Based on the assumptions above, dimensionless governing equations can be written as (Tagawa *et al.* 2002)

Continuity equation:

$$\nabla \cdot \vec{v} = 0 \tag{1}$$

Momentum equation:

$$\frac{\partial \vec{v}}{\partial t} + \vec{v} \cdot \nabla \vec{v} = -\nabla p + Pr\nabla^2 \vec{v} - \gamma Ra Pr T \nabla b^2 \tag{2}$$

Energy equation

$$\frac{\partial T}{\partial t} + \vec{v} \cdot \nabla T = \nabla^2 T - \nabla_\tau \cdot \vec{q}_r \tag{3}$$

Radiative transfer equation (for absorbing-emitting medium)

$$\frac{dI}{d\tau} = -I + \Theta^4 \tag{4}$$

The radiative heat flux can be expressed in vector form as $\vec{q}_r = q_x \vec{i} + q_y \vec{j}$, where the two components q_x and q_y can be calculated as following:

$$q_x = \int_{4\pi} I(\Omega)\mu d\Omega = \sum_{m=1}^{M} \mu_m I(\Omega_m) W(\Omega_m) \tag{5}$$

$$q_y = \int_{4\pi} I(\Omega)\eta d\Omega = \sum_{m=1}^{M} \eta_m I(\Omega_m) W(\Omega_m) \tag{6}$$

In these equations, the Prandtl number, Rayleigh number, strength of the magnetic force, and Planck number are defined respectively as:

$$Pr = \frac{\nu_0}{\alpha_0},\quad Ra = \frac{g\beta' \Delta T L^3}{\nu_0 \alpha_0},\quad \gamma = \frac{\chi_m B_0^2}{\mu_m g L},\quad Pl = \frac{k/L}{4\sigma T_{ref}^3}.$$

The microgravity condition holds here (g = 0), so Ra becomes zero and γ becomes infinity, but their product, the magnetic Rayleigh number $\gamma Ra = \dfrac{\chi_m B_0^2 \beta' \Delta T L^2}{\mu_m \nu_0 \alpha_0}$, is finite and can be used to characterize the magnetic effect (Bednarz *et al.* 2009). The Planck number is a measure of the conductive heat transfer relative to the radiative heat transfer. As the thermal conductivity k increases, the Planck number also increases and the radiation effects become less noticeable. In this paper, Pl and Pr are set to 0.02 and 0.72 respectively as (Yücel *et al.* 1989).

2.3 Boundary Conditions

Velocity is set to zero at all the walls (the no-slip condition is used). The left side wall is cold, T_c^+, and the right side is hot, T_h^+, T_c^+/T_h^+ = 0.5. We suppose the dimensionless temperature T = -0.5 at $x = 0$ and T = 0.5 at $x = 1$. The other walls are adiabatic, $(\vec{q}_c + \varepsilon \vec{q}_r) \cdot \hat{n}$ = 0. All the walls are black, so $I(\Omega) = \Theta^4$, for $\hat{n} \cdot \Omega > 0$.

Dimensionless combined heat flux on the boundary:

$$\vec{q}_T \cdot \hat{n} = (\vec{q}_c + \vec{q}_r) \cdot \hat{n} = (-\nabla T + \vec{q}_r) \cdot \hat{n}$$

We define the total Nusselt number, convective Nusselt number, and radiative Nusselt number as follows:

$$Nu_T = \vec{q}_T \cdot \hat{n}, \; Nu_c = \vec{q}_c \cdot \hat{n}, \; Nu_r = \vec{q}_r \cdot \hat{n}$$

2.4 Numerical Methods

The fluid flow and temperature field are calculated by the Code_Saturne (Code_Saturne 2004) software in which our own radiation code is implemented. We have selected the implicit Euler scheme in time, the finite volume method for the discretization in space, the second-order upwind scheme for the convective term, and the multigrid algorithm for pressure. The radiative transfer equation is solved by the discrete ordinate method (DOM) (Fiveland 1984). In this article, the angular space is discretized by S6 quadrature. The spatial domain is discretized by a non-uniform grid of 50×50 with coarser grids in the core and finer grids near the boundary.

3. Results and Discussion

3.1 Uniform Magnetic Gradient

To our best knowledge, we have not found any experimental or theoretical results that deal with the effect of radiation on thermo-magnetic convection in a participating paramagnetic medium. However, if we suppose the magnetic gradient is constant (∇b^2 = 1) and take γRa as the characteristic number, the governing equations of thermo-magnetic convection are the same as those of gravitational natural convection. In this case, the fluid flow and temperature will present a certain degree of similarity between the two.

The streamlines and isotherms of γRa $=10^6$ are shown in Fig. 4. When the radiation effect is neglected, the temperature and flow fields are centrosymmetric. The temperature is stratified uniformly in the domain. The core of the flow is multicellular, and the outer convective roll rotates in a clockwise sense, which can be seen in

Fig. **2**. The boundary layer structure exits near the active walls (hot and cold walls), so large gradients of temperature and velocity are observed.

When the radiation effect is considered, the flow pattern and temperature field are significantly changed and the symmetry disappears. For all optical thicknesses, the flow becomes unicellular and stronger as optical thickness increases. The heat transfer is enhanced because of radiative transfer, so the temperature increases considerably in the center of the cavity. However, for an optically thicker medium τ = 10.0, the penetration of the hot wall radiation into the medium is weak, so the temperature on the top wall is less than for two lesser optical thicknesses, τ = 0.1 and τ = 1.0. The same conclusion could also be drawn from the temperature distribution along the vertical and horizontal centre lines of the square cavity shown in Fig. 3. The fluid flow is also enhanced by radiation. As τ increases, the velocity increases globally as shown in

Fig. **2**. Large velocity gradients exit along all the walls. The average Nusselt numbers on the hot and cold walls are shown in Table 1. The relative error is quite small (less than 0.15%), so the numerical calculation is converged. From Table 1 we can see that as the magnetic Rayleigh number γRa increases, the fluid flow becomes stronger, and so the convective Nusselt number Nu_c and total Nusselt number Nu_T increase significantly in keeping with the same optical thickness τ . At the same time, the radiative Nusselt number Nu_r remains nearly constant. For any γRa , in comparison with pure thermo-magnetic convection, the radiative effect enforces the heat transfer in the domain, so Nu_T increases largely. As τ increases, Nu_T decreases immediately because the penetration of the hot wall radiation into the medium is weaker and the radiation effect tends to behave as conduction. The same trend could also be found from the distribution of the local Nusselt number, which is shown in Fig. 6. $Nu_r(y)$ decreases continually while $Nu_c(y)$ keeps constant.

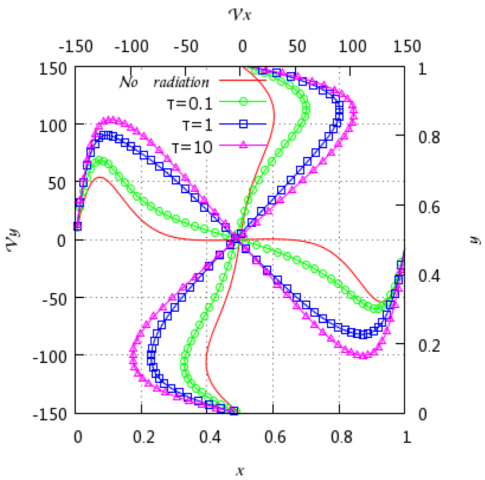

Fig. 2. Velocity distribution at x=0.5 and y=0.5 (γRa =10^6)

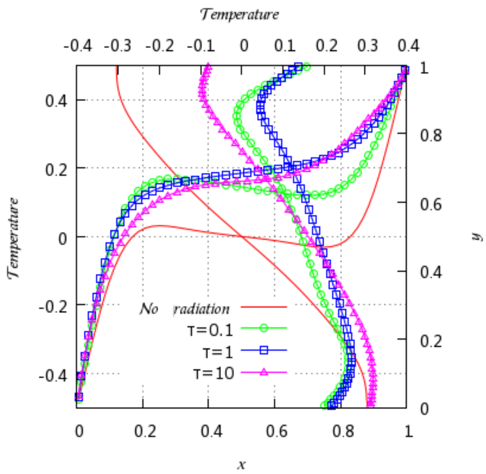

Fig. 3. Temperature distribution at x=0.5 and y=0.5 (γRa =10^6)

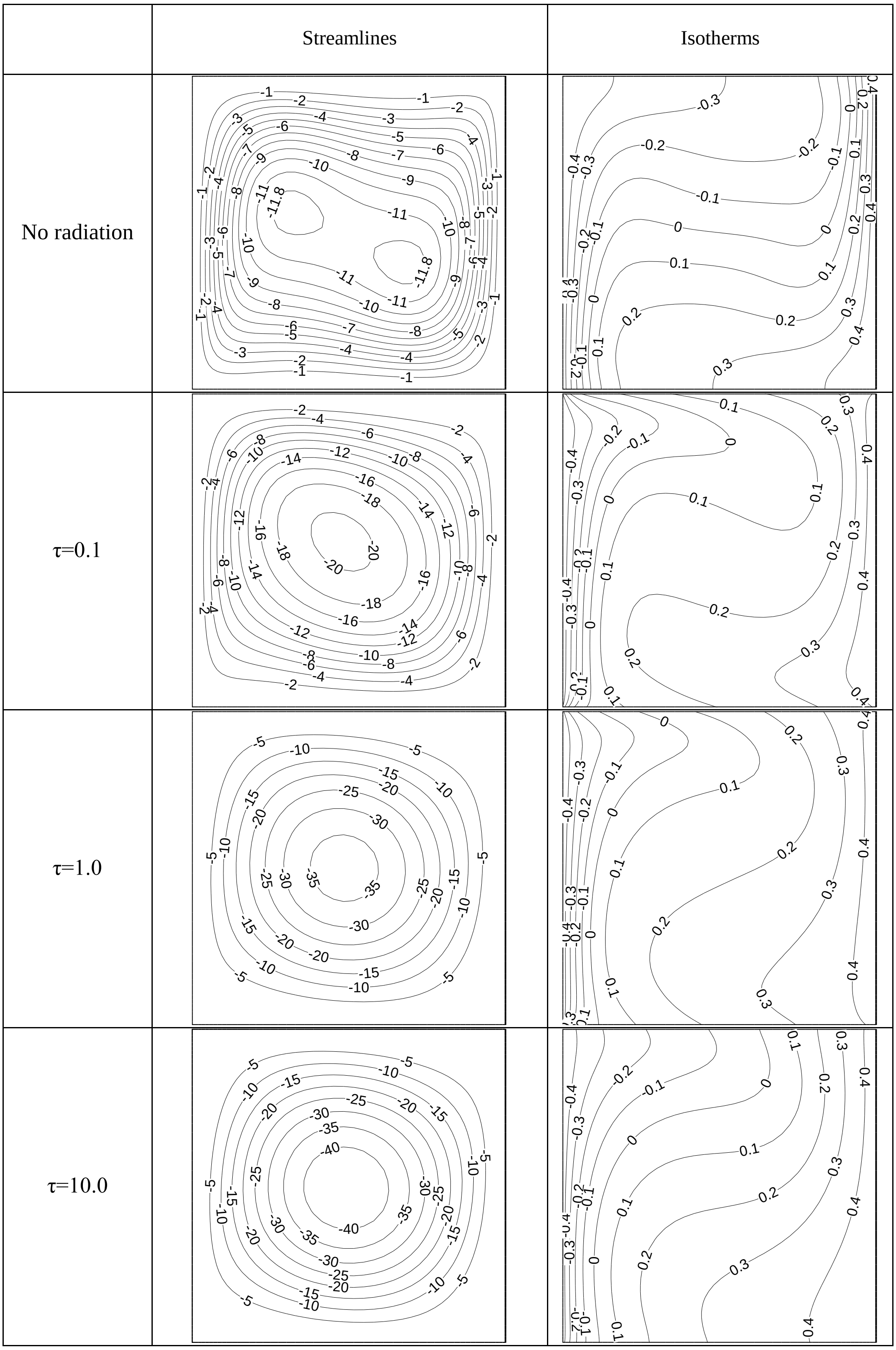

Fig. 4. Streamlines and isotherms (γRa =10^6)

Table 1 Average Nusselt number

Magnetic Rayleigh number	Optical thickness	Hot wall			Cold wall			Relative error
γRa	τ	Nu_c	Nu_r	Nu_T	Nu_c	Nu_r	Nu_T	Nu_T %
10^5	---	1.9665	---	1.9665	1.9665	---	1.9665	0
	0.1	1.8644	36.6982	38.5626	4.0987	34.4077	38.5064	0.1457
	1	2.5457	25.3229	27.8686	5.4311	22.4375	27.8686	0
	10	1.9478	6.0478	7.9956	4.2631	3.7331	7.9962	0.0075
10^6	---	3.9425	---	3.9425	3.9425	---	3.9425	0
	0.1	2.7085	37.2261	39.9346	5.6434	34.2531	39.8965	0.0954
	1	2.8942	26.5793	29.4735	6.4441	23.0290	29.4731	0.0014
	10	3.0845	9.3354	12.4199	6.4931	5.9240	12.4171	0.0225
10^7	---	7.8463	---	7.8463	7.8463	---	7.8463	0
	0.1	4.8994	37.9324	42.8318	8.9179	33.9029	42.8208	0.0257
	1	4.2974	29.0636	33.3610	9.4387	23.9222	33.3609	0.0003
	10	5.2118	14.7075	19.9193	10.4715	9.4476	19.9191	0.0010

Table 2 Average Nusselt number

Magnetic Rayleigh number	Optical thickness	Hot wall			Cold wall			Relative error
γRa	τ	Nu_c	Nu_r	Nu_T	Nu_c	Nu_r	Nu_T	Nu_T %
10^5	---	1.5004	---	1.5004	1.4988	---	1.4988	0.1066
	0.1	1.8709	36.5834	38.4543	3.9261	34.5113	38.4374	0.0439
	1	2.5414	25.2948	27.8362	5.4150	22.4212	27.8362	0
	10	1.8910	5.8812	7.7722	4.1540	3.6148	7.7688	0.0437
10^6	---	3.8588	---	3.8588	3.8583	---	3.8583	0.0130
	0.1	3.5944	36.7676	40.3620	5.5499	34.7992	40.3491	0.0320
	1	2.9663	26.1288	29.0951	6.1948	22.9002	29.095	0.0003
	10	2.4173	7.3721	9.7894	5.2194	4.5687	9.7881	0.0133
10^7	---	7.8316	---	7.8316	7.8316	---	7.8316	0
	0.1	7.2700	36.8982	44.1682	9.0945	35.0709	44.1654	0.0063
	1	5.4838	28.2432	33.7270	9.3827	24.3442	33.7269	0.0003
	10	4.6605	12.3686	17.0291	9.1212	7.9078	17.0290	0.0006

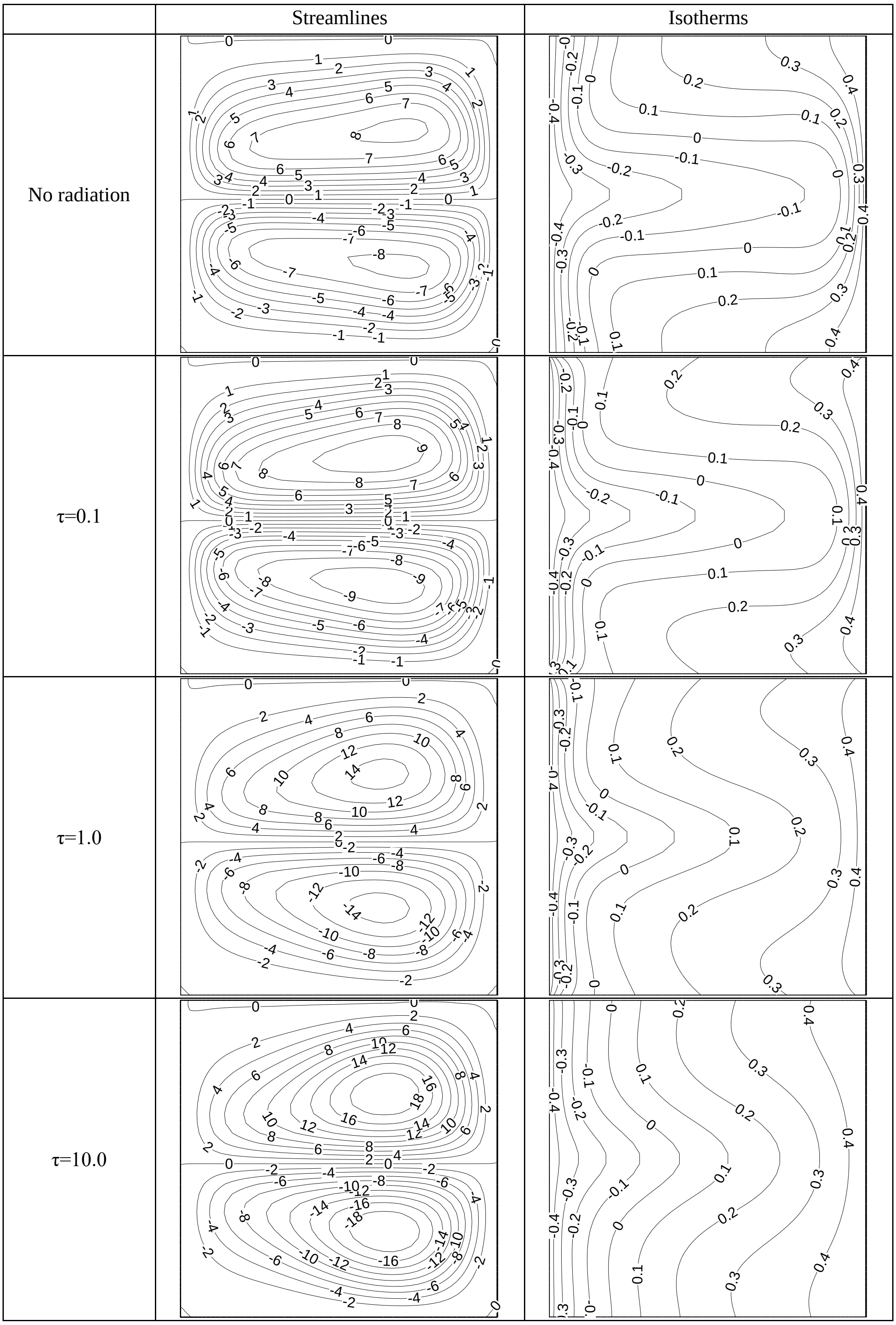

Fig. 5. Streamlines and isotherms (γRa =10^6)

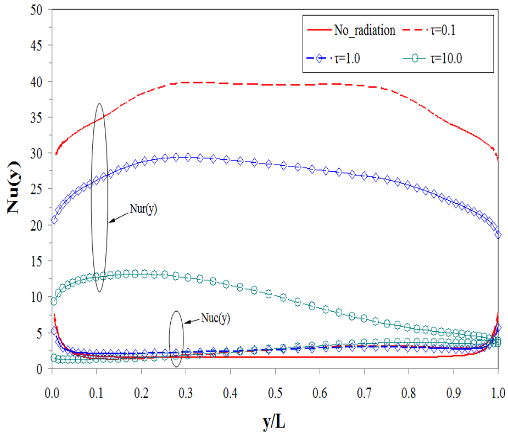

Fig. 6. Local Nusselt number $Nu(y)$ on the hot wall (γRa =10^6)

3.2 Non-Uniform Magnetic Gradient

We now turn to a more complex situation where a non-uniform magnetic gradient exists. The magnetic induction is presumed to vary symmetrically relative to the horizontal centre line in the y direction with the formulation as (Sophy *et al.* 2005):

$$B = B_0 \exp\left\{4\ln\left(10^{-2}\right)\left(\frac{y}{L}-\frac{1}{2}\right)^2\right\} \tag{7}$$

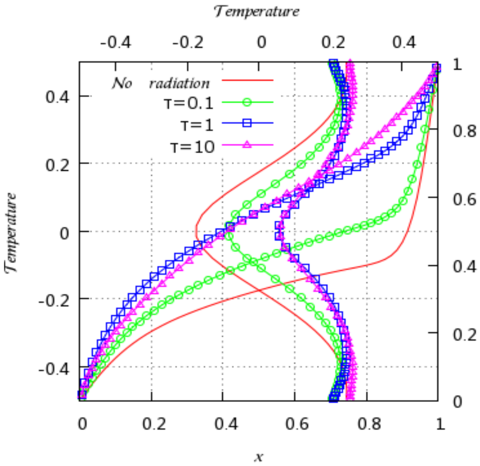

Fig. 7. Temperature distribution at x=0.5 and y=0.5 (γRa =10^6)

Because the boundary conditions for velocity and temperature are also imposed symmetrically relative to the horizontal centre line, the streamlines and isotherms of γRa =10^6 are quasi-symmetric, as shown in Fig. 5. For all the cases, with or without considering the effect of radiation, the figures are quite similar to each other. The flow pattern always remains bicellular, and each cell situates in the upper and lower space respectively. The cell in the upper half rotates in a counterclockwise direction, and that in the other half rotates in the reverse direction. In comparison with pure thermo-magnetic convection, the radiative transfer enhances the heat transfer. As a result, the heat from the hot wall can penetrate deeply in the domain, and the temperature increases largely in the vicinity of the horizontal center line. With the increasing of optical thickness τ, the distortion of the isotherm contour becomes less and less and the gradient of temperature on the hot wall decreases. The distributions of temperature and velocity along the horizontal and vertical centre lines of the cavity are shown in Fig. 7 and Fig. 8. As τ increases, the velocity increases globally. Because of the symmetric flow pattern, the flow is at rest along the y direction, so v_y is small in comparison with v_x. In contrast, temperature increases significantly until a certain τ and changes little thereafter.

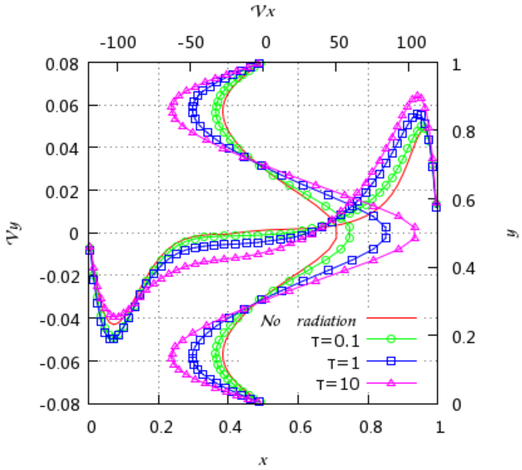

Fig. 8. Velocity distribution at x=0.5 and y=0.5 (γRa =10^6)

The average Nusselt numbers on the hot and cold walls for the non-uniform magnetic gradient case are shown in Table 2. The numerical calculation is converged with a maximum relative error less than 0.11%. The change law of Nu_c, Nu_r and Nu_T with magnetic γRa is identical to that of the uniform magnetic gradient case. The distribution of the local Nusselt number $Nu(y)$ along the hot wall is symmetric relative to the horizontal centre line in Fig. 9.

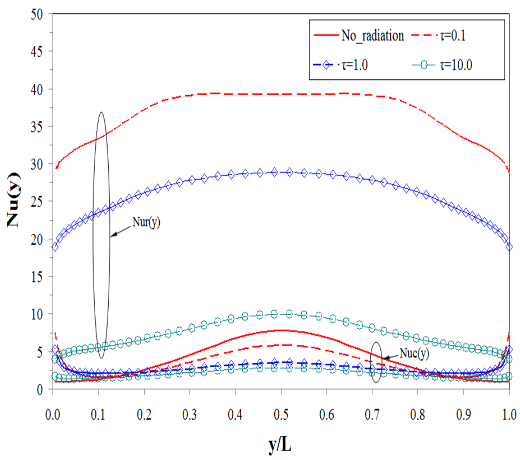

Fig. 9. Local Nusselt number $Nu(y)$ on the hot wall (γRa =10^6)

4. CONCLUSION

In this work, the study of the radiation effect on thermo-magnetic convection in a participating paramagnetic medium under microgravity conditions was carried out by a numerical simulation. An external magnetic field with uniform or non-uniform magnetic gradient was imposed. By changing the magnetic Rayleigh number and optical thickness, the streamlines, isotherms, average Nusselt number, and local Nusselt number on the active walls were calculated and analyzed in detail. The results show that both the magnetic force and thermal radiation could enhance the fluid flow and heat transfer significantly. However, as optical thickness τ increases, the Nusselt number decreases immediately while the velocity increases globally, so we could conclude that radiation also has a certain suppression effect on heat transfer but an enhancement on the thermo-magnetic convection.

This work is still exploratory, and further research is needed. For example, we will consider the coupled problem of radiation and thermo-magnetic convection in a more realistic situation, such as in a three-dimensional cubic cavity or in a gravitational field in which the magnetic force and gravity exist together.

ACKNOWLEDGEMENTS

This work was supported by Natural Scientific Research Innovation Foundation in Harbin Institute of Technology (HIT.NSRIF.2014132), Program for New Century Excellent Talents in University (NCET-12-0152), scientific research foundation of Harbin Institute of Technology at Weihai (HIT(WH)201302).

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