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Numerical simulation of the Rayleigh-Benard convection under the influence of magnetic fields

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ABSTRACT

Through performing numerical simulations, the three-dimensional thermally driven flows, namely the Rayleigh-Benard convection (RBC hereafter) flows, have been studied under the influence of magnetic field in the confined rectangular enclosure full of liquid metal. To validate our numerical methodologies, some of our numerical solutions are compared with the available experimental results that good agreements are found between them. Besides, the correlations between the Nusselt number (*Nu* hereafter) and the Rayleigh number (*Ra* hereafter) are also in accordance with the experimental results, whereas the Hartmann number (*Ha* hereafter) keeps constant. Nevertheless, in the present study, a new correlation law between *Nu* and varied *Ha* is established when *Ra* is fixed, this formula is more helpful when particularly considering the influence of the magnetic field. Regarding the horizontal magnetic field, it is found that the evolution of *Nu* versus magnetic intensity can be divided into three stages: when *Ha* is small, *Nu* increases with *Ha* because the three-dimensional RBC flow transits to transient-two dimensional pattern; when *Ha* is moderate, *Nu* increases with *Ha* because the transient-two dimensional flow is more stable that the dynamic motion of vortex cells is disappeared gradually; when *Ha* continues to increase, *Nu* still increases with *Ha* due to the growth in number of the convective cells. It should be noted that such transient process of the flow field can be hardly observed in the experiments, because the liquid metal is opaque, however, we are able to present the evolutions of the temperature fields as well as the flow structures with the help of numerical techniques.

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1. Introduction

It has been a long time since the year of 1990 that the RBC flows was studied by either experimental or theoretical methods. This phenomena, as frequently encountered in the nature and industrial applications because of the temperature difference, has exited a lot of interest in many research fields, such as the mantle movement, the weather forecast and the gas storage [1–4]. Moreover, in the metallurgical and casting industry, where liquid metals are used as working medium, RBC is always significant because of the temperature difference across the liquid layer. In such cases, whereas the external magnetic fields are always employed for flow control, the different RBC flow patterns under the influence of Magnetohydrodynamics (MHD) effect should be considered seriously.

This kind of flow was firstly observed by Benard et al. in the early 1900th, and was further analysed theoretically by Rayleigh in 1916th. Through experimental studies, it reveals that the emergence of the vortex cells, which are the typical flow structures in the RBC flows, marks a turning point where thermal convection flow happens. The number of the vortex cells will decrease with the increase of *Ra* [5,6]. Afterwards, this kind of flow transition has been widely studied because it presents a typical transition process from static flow to turbulence. In addition, another important characteristic of the RBC flows, that is the heat transfer efficiency, has also been studied extensively. It is found that in the initial stage when thermal convection emerges, the overall heat transfer will be gradually enhanced as the *Ra* increases; furthermore, in the following stage, the enhancement of heat transfer will be more rapid [7–9]. Meanwhile, some heat transfer laws applicable for different situations are put forward, especially in cases of high *Ra*. When $Ra > 10^7$, it is found that *Nu* varies with $Ra^{2/7}$ in experimental studies [10], and subsequently, the power of 2/7 is validated theoretically by analyzing the interactions between the boundary layer and the internal fluids [11–13]). When *Ra* is ultra-high, such that $10^{15} < Ra < 10^{20}$, the boundary layer is broken up by turbulence and the heat flux is very sensitive to the thermal

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dissipation and momentum dissipation, in such case another correction of $Nu \sim (PrRa)^{1/2}$ is usable [14], where Pr is the Prandtl number.

On the other hand, when external magnetic field is applied, the transition of the RBC flows under the influence of MHD effect has been of great interest in the recent years. Under vertical magnetic field, heat convection will be greatly restrained because of the Joule dissipation. By keeping the magnetic strength fixed, Burr et al. [15] established two heat transfer laws suitable for different parameter spaces of Ra, that is $Nu \sim Ra_r^{3/2}$ for $Ra_r < 2$ and $Nu \sim Ra_r^{2/3}$ for $Ra_r > 2$ respectively, where $Ra_r = Ra/Ra_c - 1$ and Ra_c is the critical Ra for vortex cells emergence. Similarly, Aurnou [16] proposed another correlation of $Nu \sim (Ra/Q)^{1/2}$ applicable for cases of $Ra/Q > 25$, where Q is the Chandrasekhar number. Nevertheless, the above heat transfer laws are only valid with constant Ha, however, with varied Ha, corrections applicable for universal situations have not been put forward yet.

Regarding the variations of the flow structures under the influence of vertical magnetic field, the number of vortex cells are increased with stronger magnetic field if the lateral channel walls are infinite, and the width of the vortex cells complies with $D \sim Ha^{-1/3}$ [17,18]). Meanwhile, the local fluctuations of the temperature field were found to be suppressed by the magnetic field, as observed in experiments [15], in which the long waves were greatly influenced while the short waves are hardly influenced. Besides, the transitions of the flow structures need to be further studied because the liquid metal is opaque in the experimental studies.

In the present study, a serials of numerical simulations are carried out to research the RBC flows under the influence of magnetic field, regardless of its strengths or directions. Simultaneously, the overall heat transfer is also computed, in order to construct a new heat transfer law which is applicable in universal cases with fixed Ra. By showing the evolution of the flow structures under different magnetic fields, we try to interpret the physical mechanics hidden behind the observations and numerical results.

Concerning the RBC flows under the influence of horizontal magnetic field, it is found that the three-dimensional instability of the convection flow is significantly inhibited by the magnetic field, combined with the enhancement of the heat transfer, and it is thought to be related with the inertial convection model. Another particular observation is that the vortex cells will be more and more parallel with the magnetic direction [17].

In Section 2 of this paper, the three dimensional physical model is established, presenting the physical problems we try to study. In Section 3, the governing equations, as well as the numerical approaches are introduced. In Section 4, the numerical results under the influence of the magnetic fields, together with the comparisons with the available experimental or theoretical results, are present. Detailed analysis are also given in this section. In the last section, a conclusion part is followed.

2. Numerical model

The liquid metal confined in a rectangular cavity is studied in the present study, while the external magnetic field is imposed either in a vertical or horizontal directions, as shown in Fig. 1. The dimension of the cavity is set with $L \times L \times H = 8.0 \times 8.0 \times 1.0$, where L is the side-length and H is the height of the cavity. It should be noted that the aspect ratio of the cavity is rather important in generating different vortex structures of the RBC flow, as being extensively investigated in many literatures, either about the small aspect ratios [6,19] or the large aspect ratios [20,21]. However, it is beyond the scope of the present study, and we just focus on one figuration of the cavity. Besides, concerning the temperature field, the side walls of the cavity are assumed to be adiabatic while constant temperatures are given at the top wall and the bottom wall, with T_t and T_b respectively. To generate the RBC flow, T_t is set to be higher than T_b that the temperature difference between them, namely Δt, provides the driving force for such convective flows.

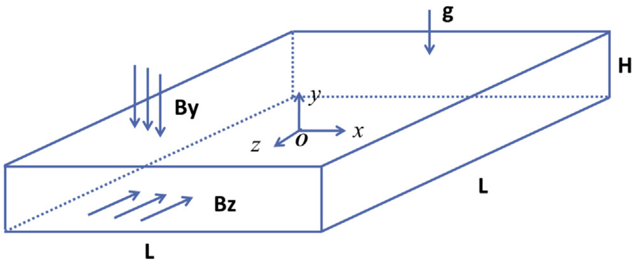

Fig. 1. Physical model of the RBC flows under the influence of magnetic field.

Throughout the numerical study, liquid Gallium is employed as the working medium, the physical properties of which are present in Table 1, where ρ is the density, β is the thermal expansion coefficient, μ is the dynamic viscosity, κ is the thermal diffusion coefficient and σ is the electric conductivity. Besides, the subscript 0 indicates the reference physical properties at $T = T_t$.

3. Governing equations

The widely used Boussinesq assumption is valid in the present study that except the density ρ, other physical properties of the liquid Gallium keep constant in the inhomogeneous temperature field. Correspondingly, the density is calculated as $\rho = \rho_0[1 - \beta(T - T_t)]$ in the gravitational term while it is still $\rho = \rho_0$ in other terms. In addition, when considering the magnetic influence, the induced magnetic field can be ignored in comparison with the external magnetic field due to the small magnetic Reynolds number $Re_m = \mu\sigma H v_0 \approx 3.06 \times 10^{-3}$ [22], whereas v_0 is the dimensionless velocity. According to the above assumptions, the equations governing the MHD RBC flows can be summarised as:

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

$$\frac{\partial \vec{V}}{\partial t} + (\vec{V} \cdot)\vec{V} = -\frac{1}{\rho_0}\nabla P + \frac{1}{\rho_0}(\vec{j} \times \vec{B}) + \nu\Delta\vec{V} - [1 - \beta(T - T_t)]g = 0 \tag{2}$$

$$\vec{j} = \sigma(-\nabla\varphi + \vec{V} \times \vec{B}) \tag{3}$$

$$\nabla \cdot \vec{j} = 0 \tag{4}$$

$$\frac{\partial T}{\partial t} + \vec{V} \cdot \nabla T = \kappa\Delta T \tag{5}$$

Table 1
The physical properties of the liquid gallium [16].

Physical property	Value	Units
ρ_0	6.095×10^3	kg/m^3
β	1.27×10^{-4}	K^{-1}
μ_0	1.95×10^{-3}	kg/(m · s)
κ_0	1.27×10^{-5}	m^2/s
σ_0	3.85×10^6	S/m
H	1.82×10^{-2}	m

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