DNS OF NATURAL CONVECTION IN LIQUID METAL WITH SRTONG MAGNETIC FIELD IN RECTANGULAR BOX

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Abstract Direct numerical simulations of natural convection in liquid metal within rectangular box heated uniformly from below with uniform strong vertical magnetic field are conducted. The main aim is to explore the possibilities and mechanisms of convection instabilities in such flows. The effects of parameter range on the flow structure, i.e. variations in Hartmann number, Rayleigh number and aspect ratio, are analyzed. It is shown that the magnetic field can completely change the structure and orientation of convection rolls by leading a new flow structure lined magnetic field. And if the magnetic field is strong enough, convection in the system can be fully suppressed.

INTRODUCTION

The subject of the topic is interaction between buoyancy-induced flow and strong magnetic field. It is known that turbulence can be fully suppressed by strong magnetic field, leading to a laminar regime. However, this does not mean that laminar steady-state regime is always correct. The results in experiment [1] which considered the flow through a pipe both with magnetic field and temperature gradient, showed temperature fluctuations disappeared at moderate strong magnetic fields, but reappeared at stronger magnetic fields in form of high-amplitude low-frequency oscillations indicating convection-related instabilities may occur. This phenomenon is expected to appear in all systems with strong magnetic fields and buoyancy effects, particularly, in case of liquid metal blankets of a fusion reactor, where Ha and Ra are very high. A detailed investigation of thermal convection in liquid metal flows with strong magnetic fields appears necessary. In this work, we consider the influence of strong magnetic field on natural convection in liquid metal within a rectangular box, which is relevant to the situation with weak or zero imposed flow, for example, in the case of the HCLL blanket, where the liquid metal is used only for breeding. We are focus on fundamental analysis rather than on specific applications. As shown in figure 1, we consider flows in a closed box with imposed vertical magnetic field B and vertical temperature gradient created by setting upper and bottom walls maintain constant and different temperatures. The other four walls are thermally insulated and all walls are perfectly electrically insulating. We consider the fluid as an electrically conducting, incompressible, Newtonian fluid, with constant physical properties. The Boussinesq approximation is applied for the temperature-related buoyancy force. And we assume that the magnetic Reynolds number and the magnetic Prandtl number are both much smaller than one. The non-dimensional governing equations of the problem are:

$$\nabla\cdot\boldsymbol{u}=0$$

$$\frac{\partial\boldsymbol{u}}{\partial t}+(\boldsymbol{u}\cdot\nabla)\boldsymbol{u}=-\nabla p+\left(Re^{*}\right)^{-1}\nabla^{2}\boldsymbol{u}+\boldsymbol{F}_{b}+\boldsymbol{F}_{L}$$

$$\frac{\partial\theta}{\partial t}+(\boldsymbol{u}\cdot\nabla)\theta=\left(Re^{*}Pr\right)^{-1}\nabla^{2}\theta$$

$$\boldsymbol{j}=-\nabla\phi+\boldsymbol{u}\times\boldsymbol{e}_{b},\ \nabla^{2}\phi=\nabla\cdot\left(\boldsymbol{u}\times\boldsymbol{e}_{b}\right)$$

Where, the buoyancy and Lorentz forces are defined as $\boldsymbol{F}_b=-Re^{*-2}Pr^{-1}Ra\theta\boldsymbol{e}_g$, $\boldsymbol{F}_L=Re^{*-1}Ha^2\boldsymbol{j}\times\boldsymbol{e}_b$. In our case there is no imposed flow, so we have defined a special Reynolds number as $Re^*\equiv\sqrt{\frac{Ra}{Pr}}$. Then the non-dimensional parameters of the problem are the Rayleigh number $Ra\equiv\frac{g\alpha\delta TH^3}{\kappa\nu}$, Prandtl number $Pr\equiv\frac{\nu}{\kappa}$, the Hartmann number $Ha\equiv B_0H\sqrt{\frac{\sigma}{\rho\nu}}$ and the space ratio $\Gamma\equiv Lx:Ly:H$. The problem solved by direct numerical simulation and the numerical model is based on the projection-type and nearly fully conservative finite difference scheme described in [2]. The effects of parameter range on the flow structure, i.e. variations in Hartmann number, Rayleigh number and aspect ratio, are analyzed.

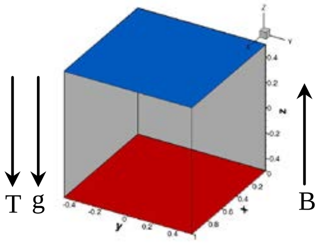
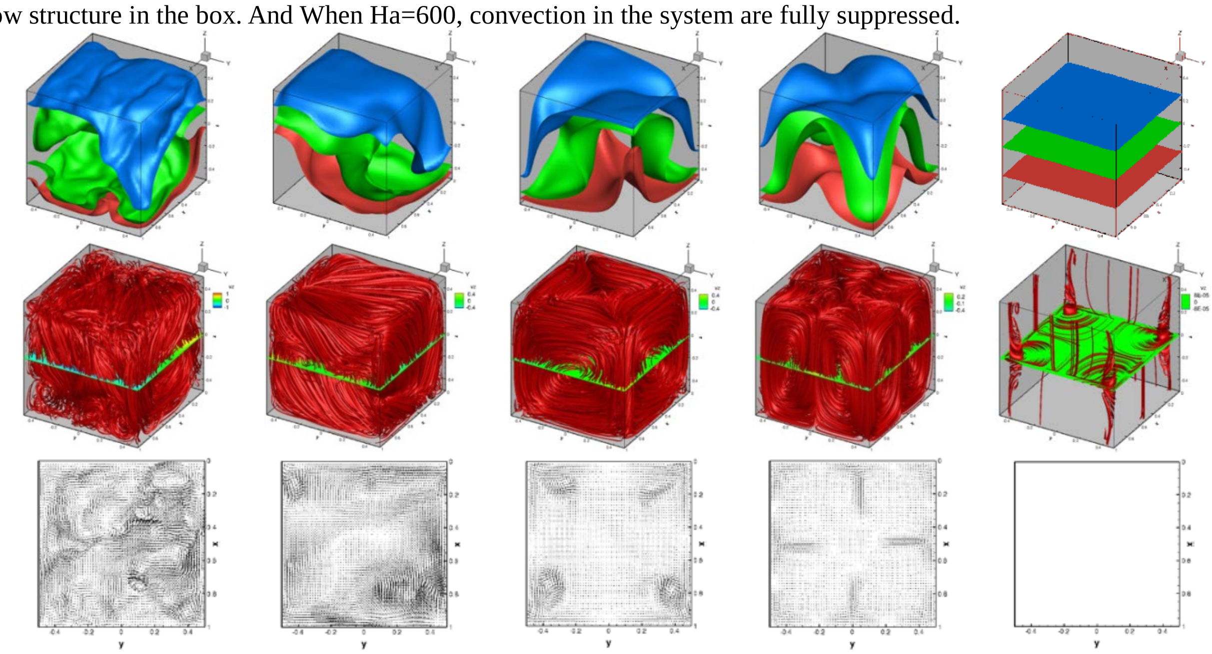


Figure 1. Sketch of the geometry.

RESULTS

The simulation results of convection in a cubic box with different vertical magnetic field are shown here. Single values Pr=0.025, Ra=10^6 are used in the analysis. And the resolution here is 128x128x128. The direction of the magnetic field is z direction. The Hartmann number varies in the range between 50 and 600. Figure 2 shows the final state of convection in cubic box with different magnetic field and figure 3 shows the fluctuating temperatures at the center of the box. It is shown that the magnetic field can completely change the structure and orientation of convection rolls by leading a new flow structure lined magnetic field. When Ha=300, the temperature field become steady, but there is still flow structure in the box. And When Ha=600, convection in the system are fully suppressed.



(a) Ha=0 (b) Ha=100 (c) Ha=200 (d) Ha=300 (f) Ha=600

Figure 2. Convection in a cubic box with different vertical magnetic field
Upper row: iso-temperature field; middle row: streamtraces; lower row: velocity vector on mid-xy plane

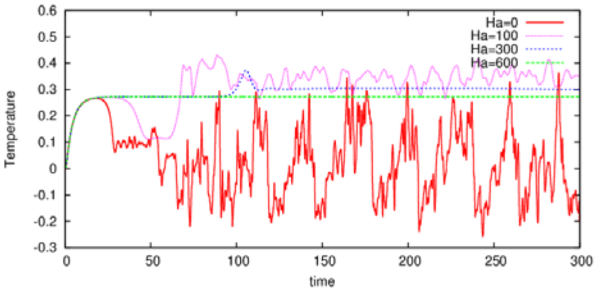


Figure 3. Fluctuating temperatures at the center of the box with different vertical magnetic field

References

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