MAGNETO-HYDRODYNAMIC INTERACTION IN A VERTICAL SLOT FILLED WITH FERROFLUID

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Abstract: Convection flow in a vertical layer of ferrofluid heated from a side and subject to the transverse magnetic field is studied. A stability map is computed and compared with experimental flow visualizations. It is shown that the excitation of magneto-convection leads to the formation of vertically aligned rolls. The interaction of thermo-gravitational and thermo-magnetic motions results in roll and wave patterns of various spatial orientations. A new thermo-magnetic wave instability mechanism is found to exist for sufficiently large values of magnetic Grashof number.

1. Introduction

Theoretical investigation of ferrofluid convection in a differentially heated vertical layer in a horizontal transverse magnetic field has been reported previously [1, 2]. Disturbances in the form of horizontal rolls similar to those found in conventional large-Prandtl-number fluids were found. Early experiments conducted in relatively thick (few centimeters) layers [3] did not reveal a significant influence of a magnetic field on convective instability and heat transfer either: the flows were dominated by thermo-gravitational effects. On the other hand, a series of more recent experiments conducted in thin ferrofluid layers with large magnetite concentration and subject to transverse uniform magnetic field [4, 5] showed that magneto-convection plays a dominant role in this geometry. The resulting convection patterns were found to be drastically different from those expected to exist in a vertical differentially heated layer due to thermo-gravitational instability. In particular, in a large-Prandtl-number fluid, such as a kerosene-based ferrocolloid used in the cited experiments, the thermo-gravitational instability manifests itself as a pair of counter-propagating thermal waves which form horizontal convection rolls [6]. In contrast, vertical and inclined rolls were observed in thin-layer experiments. This strongly suggests that the magnetic properties of a fluid, the layer thickness and the orientation of the applied magnetic field are the major factors which define the type of the experimentally observed dominant convection pattern. The study of such influences is the major goal of the present work.

2. Major thermo-magnetic motions in a vertical ferrofluid layer

Two vertical slots with thicknesses of 3.5 mm and 5.2 mm and aspect ratios of 21 and 73, respectively, were used. The heated vertical walls were made of copper and aluminum. The opposite transparent walls were made of Plexiglas. The average temperature measures across the layer were maintained at room temperature. Since a magnetite-based fluid used in experiment is not transparent a heat-sensitive liquid-crystal film sensors with working temperature in the range 24 – 27^0C and 19 – 23^0C were glued to the inner side of transparent walls with a thin layer of epoxy resin to make observations possible. To prevent film warping and separation from a wall another plexiglas sheet was used to cover a thermosensitive layer. The presence of such a "sandwich" structure reduces temperature sensitivity and spatial resolution of a sensor. Yet it was possible to reliably register fluid surface temperature variations of several tenths of a degree. When the flow is relatively slow the relationship between the transverse velocity component and the convective distortion of the temperature field is approximately linear. Therefore color variations in a liquid-crystal thermo-indicator were compared with a non-convective state to identify the flow pattern and estimate its intensity.

Experiments were performed in a kerosene-based magnetic fluid with an average magnetite particle size of 10 nm and a magnetic phase concentration of 10 %. The fluid had the following estimated properties: fluid density $\rho = 1.25 \cdot 10^3$ kg/m^3, coefficient of thermal expansion $\beta = 0.86 \cdot 10^{-3}$ 1/K, magnetic saturation $M_S = 48$ kA/m, pyromagnetic coefficient $K =$ 80 A/m·K, dynamical viscosity in zero magnetic field $\eta = 0{,}006$ kg/(m·s), magnetic susceptibility $\chi = 5$, Prandtl number $Pr = 128$. A uniform external magnetic field was generated by Helmholtz coils. The subsequent fluid magnetization decreased the internal magnetic field. Since colder fluid is capable of a stronger magnetization the basic conduction state is characterized by an internal magnetic field which is decreasing linearly towards the cold wall [7].

The complete stability diagrams for two- and three-dimensional disturbances were computed in [7]. Sixteen regions characterized by distinct instability patterns and combinations of patterns were identified. Figure 1 presented here contains the summary of major predicted flow patterns. The non-dimensional physical parameters used in this figure are magnetic Grashof number $Gr_m = \rho\mu_0 K^2\theta^2 d^3/\eta^2\ (1+\chi)$ and gravitational Grashof number $Gr = \rho\beta\theta g d^3/\eta^2$, where μ_0 is the magnetic constant, θ is the temperature half-difference between the walls, d is the half-thickness of the layer and g is the gravity. The narrow white strip adjacent to the vertical Gr axis in fig. 1 corresponds to a stable conduction state which is characterised by linear temperature and cubic velocity profiles. The region where thermo-gravitational convection sets is labelled as TGW. The most dangerous disturbances here correspond to two counter-propagating thermal waves similar to those found in natural convection of large Prandtl number fluids [6]. The combination of two counter-propagating thermal waves results in a standing wave which consists of horizontal convection rolls periodically changing the direction of their rotation.

In the region labelled as STMR only a magneto-convective instability is present. The vertical stationary magneto-convection rolls are expected to dominate the instability pattern. This is in agreement with experimental observations shown in fig. 2. The critical wavenumbers experimentally determined for selected regimes in this parametric region agree with those computed in [7]. The combination of dominant horizontal rolls resulting from a pair of thermo-gravitational waves and stationary vertical magnetoconvection rolls defines the overall pattern in a relatively large region labelled STMR+TGW. The stationary vertical rolls and oblique waves are predicted in regions marked by STMR+TMW1 and STMR+TMW2 (which are distinguished by essentially different wavelengths of oblique rolls). Our computations suggest that the presence of oblique waves should be possible to detect by observing a relatively weak "blinking" superposed on developed vertical rolls. This was indeed observed experimentally: the example of combined patterns is shown in fig. 3.

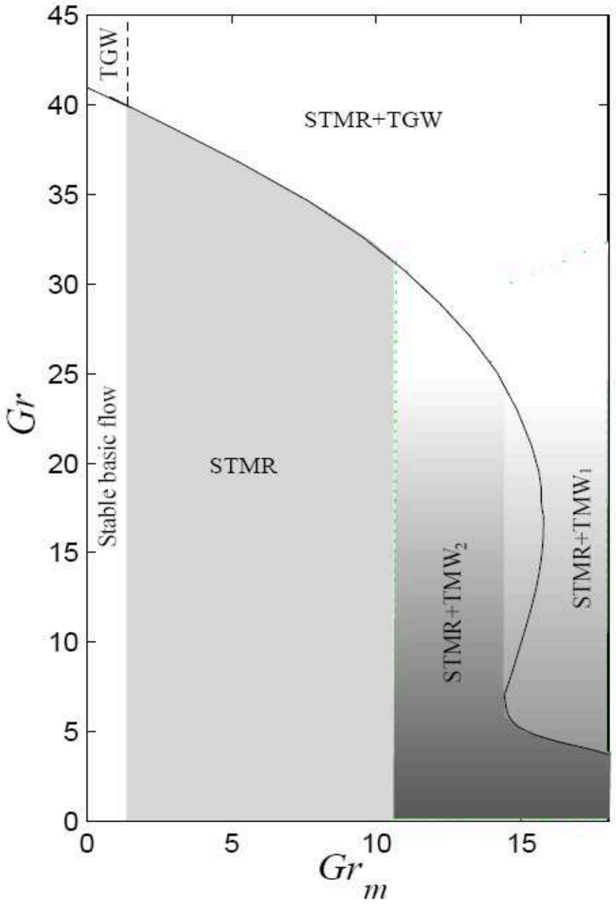

Figure 1. Summary of flow stability results for ferrofluid convection in a vertical layer placed in a perpendicular uniform magnetic field.

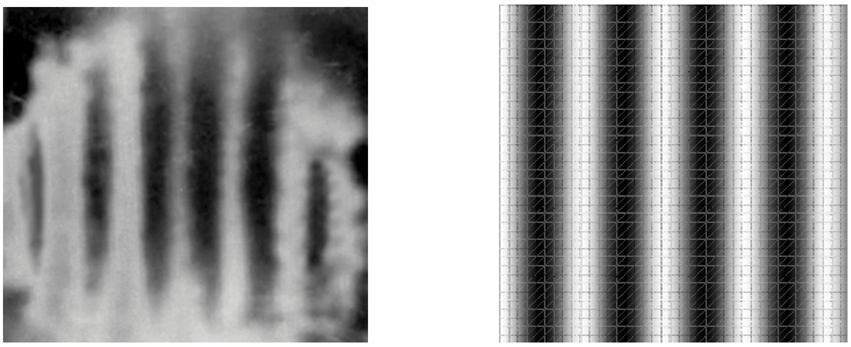

Figure 2. Magneto-convective instability: liquid crystal visualization (left) and the computed three-dimensional temperature field near the cold wall (right) for (Gr_m,Gr) = (10, 7). Magnetic field is perpendicular to the plane of snapshots.

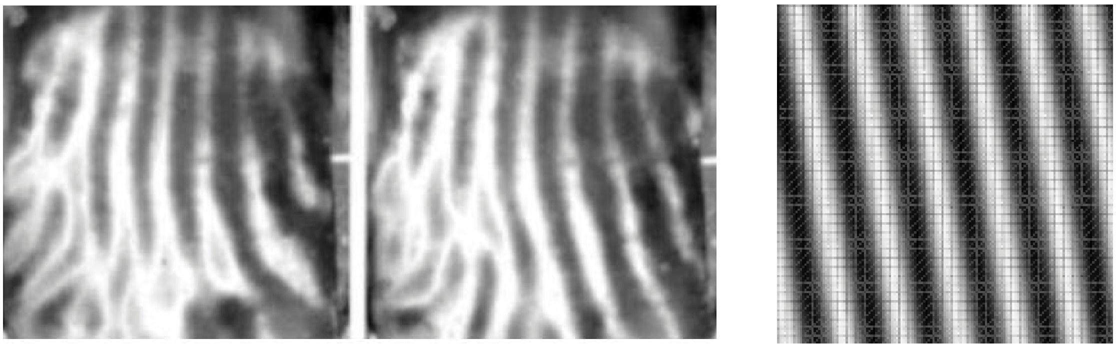

Figure 3. Oblique rolls for $(Gr_{\mathrm{m}}, Gr) = (15, 8)$: "blinking" states observed experimentally (two left snapshots) and oblique waves obtained numerically (right).

The existence of such oblique waves was found theoretically for the first time in our previous work [7]. A disturbance energy analysis conducted in our subsequent work [8] showed that their mechanism is of a thermo-magnetic character (thus the abbreviation TMW). It is different from that of thermo-gravitational waves and is illustrated in fig. 4 for time instances equally spaced over period T. A pair of waves resembling thermo-gravitational propagate upwards (downwards) along the hot left (cold right) walls. At $t = T/4$ and $t = 3T/4$ warm (cool) fluid rises (sinks) due to gravitational buoyancy as is the case in thermo-gravitational waves observed in non-magnetic high-Prandtl-number fluids. Yet the buoyancy cannot explain the motion at $t = 0$ and $t = T/2$ because at these moments warm fluid flows both up and down, see fig. 4. During these phases

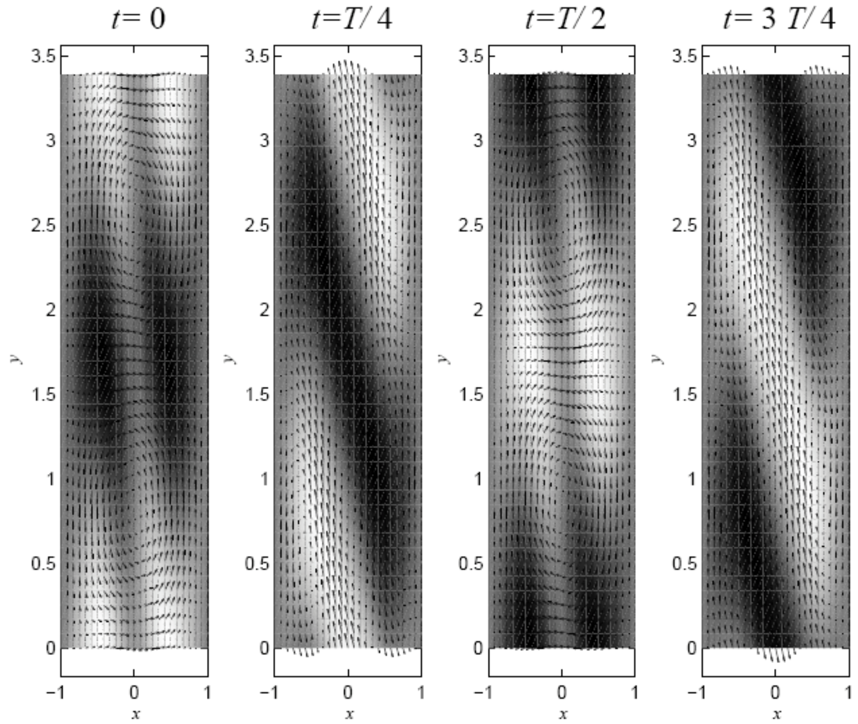

Figure 4. Snapshots of typical thermo-magnetic perturbation velocity (arrows) and temperature (gray shades) fields across the layer. Light areas correspond to warmer fluid.

convection is driven by magnetic ponderomotive forces: cool and more magnetized fluid (dark regions) is pushed towards the hot wall where the basic magnetic field is stronger. The buoyancy and magnetic effects alternate over the wave period. This is the major feature of thermo-magnetic waves distinguishing them from their thermo-gravitational counterparts: in the latter warm fluid always rises and cool always sinks. The transition between thermo-gravitational and thermo-magnetic waves is continuous and occurs when Gr and Gr_m are of comparable sizes. Therefore the regions of existence of thermo-magnetic waves are shown by gradient shading blending with thermo-gravitational wave region in fig. 1.

3. Conclusion

We found that the two base physical mechanisms, thermo-gravitational (buoyancy) and thermo-magnetic, result in three distinct types of perturbed flow patterns: counter-propagating thermal waves (large Gr, small Gr_m), counter-propagating thermo-magnetic waves (large Gr_m, intermediate Gr) and stationary magneto-convection rolls (intermediate to large Gr_m, small Gr). We also note in passing that a spatial orientation of the detected instability patterns is strongly related to the physical mechanisms causing them: the propagating thermal or thermo-magnetic instability waves form horizontal or inclined convection rolls, while stationary magneto-convection rolls are vertical.

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4. References

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