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Using magnetic liquids to simulate convection in a radial force field

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Convection in a radial force field is a central problem of convection in plantary interiors, including the Earth's core and mantle. Common laboratory experiments, however, only allow the investigation of convection in a unidirectional and constant gravity field.

Magnetic liquids are manufactured suspensions of magnetic nanoparticles in a carrier liquid of suitable choice. The particles possess a fixed magnetic moment and are coated with a surfactant to prevent coagulation. When an external magnetic field is applied, the resulting orientation of the particles results in a net magnetisation of the fluid which depends both on the applied field and the temperature of the fluid. The fluid then experiences a body force towards stronger magnetic fields, known as the Kelvin force, $f = \mu_0 M |\nabla H|$. A local variation in temperature will result in a local variation of the Kelvin force, resulting in a magnetic equivalent to natural convection.

The equivalence between natural convection and thermomagnetic convection can be quantified by equating the volume expansion coefficient, α_0, with the temperature sensititvity of the magnetisation, $(\partial M/\partial T)_H$, known as the pyromagnetic coefficient, and the gravity potential with the magnetic field, H (or gravity, g, with the field gradient, $|\nabla H|$). This leads to a thermomagnetic Rayleigh number as defined by

$$Ra_m = \frac{L^3}{\nu\kappa} \frac{\mu_0}{\rho} \left(\frac{\partial M}{\partial T}\right)_H |\nabla H| \, \Delta T, \tag{1}$$

compared to the standard Rayleigh number as

$$Ra = \frac{L^3}{\nu\kappa} \alpha_0 g \, \Delta T,$$

where L is the length scale, $\mu_0 = 4\pi \times 10^{-7}$ the permeability of free space. ν and κ are the kinematic visocity and thermal diffusivity, respectively.

Using fairly standard magnets and magnetic liquids, the pyromagnetic coefficient is $O(10\mathrm{Am}^{-1}\mathrm{K}^{-1})$, and field gradients can be $O(10^4 - 10^7\mathrm{Am}^{-2})$. This can lead to magnetic Rayleigh numbers of the same order as Ra, or even some orders of magnitude larger than the standard Rayleigh number.

In this paper, we will present a relatively simple, 2D finite-element model of a proposed laboratory experiment to use a magnetic liquid in a spherical shell, where a permanent magnet is embedded in the inner core of the experiment. This will be compared with an equivalent model assuming a central gravity field. The comparison between these two experiments will be put into the context of an existing experiment of natural and magnetic Rayleigh-Bénard convection of a magnetic liquid in a box. This experiment, and a corresponding finite-element model, have shown that convection could be initiated by the presence of a magnet on top, or to the side of the box despite a stabilising temperature gradient (i.e. cooled from below). Conversely, a magnet positioned below the box could inhibited natural convection effectively if the box was heated from below.