International Journal of Thermal Sciences 116 (2017) 118–128

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Using infrared thermography to investigate thermomagnetic convection under spatial non-uniform magnetic field

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ARTICLE INFO

Article history:
Received 24 August 2016
Received in revised form
26 January 2017
Accepted 6 February 2017

Keywords:
Magnetic fluid
Thermomagnetic convection
Kelvin body force
Magnetic Rayleigh number

ABSTRACT

Thermomagnetic convection was investigated experimentally by infrared thermography and validated numerically by a finite-element analysis. A cavity filled with a magnetic liquid was under the influence of a permanent magnet that provided an external magnetic field and was subjected to thermal forcing by maintaining the two opposite horizontal walls at different temperatures. All configurations were chosen to explore situations where the Kelvin body force and buoyancy would either oppose each other or act perpendicular to each other. As both body forces depend on temperature, the aim was to explore the degree by which heat transfer may be enhanced by only varying the temperature difference. The results demonstrate that the Kelvin body force, which can be much stronger than buoyancy, leads to convective flow where only conduction would occur without the presence of the magnet. An effective force ratio, *r*, is developed which suggests that an increase in temperature difference across the cavity initially leads to a dominance of thermomagnetic forcing over buoyancy but that the overall force balance becomes more moderate at higher temperature differences. The global effect of both body forces on heat transfer was characterised by the Nusselt number and a suitable modified Rayleigh number.

1. Introduction

Low thermal conductivity in conventional heat transfer fluids such as oil, water and ethylene glycol are a primary limitation for the development of energy efficient heat transfer that is required in many industrial applications. The capability to produce suspensions by adding nanoparticles with higher thermal conductivity, such as ferromagnetic fluids, enables a new class of heat transfer fluids [1]. A great advantage of using such fluids is not only the enhancement in thermal conductivity but also the magnetic response of the fluid that may additionally be used to create a thermomagnetically induced convective flow. Some of their applications and properties are given by Refs. [2,3].

Ferromagnetic fluids are industrial colloidal suspensions of single domain magnetic particles with an equivalent diameter of approximately 10 nm. The particles are coated with a dispersant to prevent agglomeration and coagulation by maintaining an adequate spacing between magnetic particles. This provides colloidal stability when the particles are dispersed in a carrier fluid such as water, kerosene or a silicone based fluid. As a result, the magnetic particles follow Brownian motion while the macroscopic fluid behaves as a homogeneous magnetisable fluid [3,4]. Here we have investigated the flow structure of thermomagnetic convection using infrared thermal imaging and comparing this to the results of a finite-element model of the experiment.

1.1. Thermomagnetic convection

Thermomagnetic convection refers to convective heat transfer based on a temperature gradient within a magnetic fluid that induces a local variation in the fluid's magnetisation in the presence of a magnetic field. A key feature is the temperature dependence of fluid magnetisation: thus, cooler fluid is more magnetised than hotter fluid, resulting in a magnetisation gradient imposed by temperature differences that establish flow fields where cooler fluid moves towards higher magnetic field intensity and creates convection [5–7]. The resulting thermomagnetic convection may be controlled by varying the magnetic properties of the fluid, the temperature distribution and the applied magnetic field [8].

Thermomagnetic instabilities in spatially non-uniform magnetic fields were first obtained analytically in the early 1970s by Curtis [9] and accompanied by Lalas and Carmi [10]. Since then, the literature

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http://dx.doi.org/10.1016/j.ijthermalsci.2017.02.004
1290-0729/

has grown, and thermomagnetic convection with the use of permanent magnets that comply with Maxwell's equation of electromagnetism was analysed by Ganguly et al. [6], Mukhopadhyay et al. [11] and Banerjee et al. [12]. Since then, natural and thermomagnetic convection has been studied in several geometries such as tubes [13], cylinders [14,15], cavities [16–18] and in geosciences [19]. A systematic experimental investigation of combined natural and thermomagnetic convection in a cube subjected to a magnetic field from a permanent magnet was performed by Sawada et al. [20]. Snyder et al. [21] complemented these experiments with a computational simulation for the same configurations but approximating the magnetic field through a constant gradient. While the simulations were able to reproduce single convection cells for natural convection and for convection with strong magnets, their model could not reproduce the two-cell flow structures suggested by the experimental observations.

In this study, we follow the approach taken by Sawada et al. and Snyder et al. but, instead of investigating the effect of thermomagnetic convection on natural convection on a magnetic fluid with an imposed horizontal temperature gradient, we considered a stably stratified fluid cooled from below and heated at the top. By choosing this particular configuration, the focus is not on how thermomagnetic convection can be used to enhance natural convection. Instead, the focus is on how thermomagnetic convection can act as a substitute for natural convection and how this process can be studied in an Earth-based laboratory as was proposed by Früh [19] albeit for a different purpose and context.

For the computational simulations complementing and validating the experiments, we chose not to approximate the magnetic field with a constant field gradient [21] or with an analytical solution [6,12] but to solve the magnetostatic equations within the same finite-element package as the governing equations for the heat and fluid flow.

Finally, we present infrared thermography as an alternative non-invasive technique to observe the solution structure in the fluid.

1.2. Infrared thermography for heat and fluid flow

As magnetic liquids are opaque, it is challenging to visualise the flow structures in them. Up until now, the measurements of fluid velocities in a magnetic fluid have been restricted to in-situ sensors, such as hot-film anemometry [22], or non-invasive velocity measurements such as Ultrasound Doppler velocimetry [23] or, in the case of very thin layers, micro-PIV [24]. In addition to local temperature probes, such as thermistors or thermocouples [16,25], liquid-crystal thermography has been explored to measure the temperature field in cubic enclosures [26–28] and a Hele-Shaw cell [29,30], where one side of the cell was sprayed with a temperature sensitive liquid crystal. An alternative to liquid-crystal thermography is infrared thermography whereby the temperature of an object is visualised using an infrared camera. Thermal imaging of a fluid's temperature field is easily accomplished in convection experiments with a free surface [31].

Here we present a visualisation of the temperature field in the fluid cavity through one of the cavity walls made of thin perspex. As perspex absorbs most of the thermal infrared radiation, the visualisation is in fact that of the perspex surface whose temperature reflects that of the fluid through heat conduction. However, as will be demonstrated below, the perspex temperature field reflects that of the fluid, at least on length scales similar to the perspex thickness and larger, and as long as the flow structures do not change too quickly over time.

Considering that both, the liquid-crystal method [20] and the infrared method reflect the temperature field of the fluid near the surface through which the images are recorded, the design of our experiment was based on a relatively thin square enclosure as opposed to a cubic enclosure. This was chosen with the aim to observe a representation of the bulk flow rather than a boundary layer structure of an intrinsic 3-dimensional flow.

2. Theoretical formulation

Ferromagnetic fluids have usually a very small electric conductivity and electric effects are often neglected [6,11]. In line with this, the fluid is assumed to be non-conductive and does not induce an electromagnetic current. Consequently, the magnetic field generated by the permanent magnet conforms to Maxwell's equations for non-conductive material in static form, represented as

$$\nabla \times \mathbf{H} = 0 \tag{1}$$

$$\nabla \cdot \mathbf{B} = 0 \tag{2}$$

where **H** is the magnetic field and **B** the magnetic induction. By definition the magnetic field and magnetic induction are related in the following manner

$$\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M}) \tag{3}$$

where $\mu_0 = 4\pi \times 10^{-7}$ H/m is the permeability of free space and **M** the magnetisation of the magnetic material. Hence, the magnetisation of a permanent magnet may be written as $\mathbf{M} = \mathbf{B}_r/\mu_0$ where $\mathbf{B}_r$ is the remanent flux density of the magnet. The assumed magnetic field, **H**, within the fluid domain is considered dependent on the initial Langevin susceptibility

$$\chi_L = \frac{nm^2}{3\mu_0 k_B T} \tag{4}$$

and modified after Pshenichnikov et al. [32] to include inter-particle interactions and written as

$$\chi = \chi_L(1 + \chi_L/3) \tag{5}$$

where n is the particle number density and equals to $(\mu_0\ \phi M_d/m)$, m the magnetic moment of the ferromagnetic nanoparticles, k_B the Boltzmann's constant and T the temperature. Thus, the actual magnetic field acting on the magnetic fluid may be written as

$$\mathbf{H} = \frac{\mathbf{B}}{\mu_0(1 + \chi)} \tag{6}$$

and conforms to Maxwell's equations, eqs. (1) and (2), in static form.

The strength of the magnetisation, M, for a monodispersed colloidal magnetic fluid is expressed as a function of the magnetic field intensity, the temperature and the concentration of dispersed magnetic particles. By applying Langevin's function $\mathscr{L}(\zeta) = \coth(\zeta) - 1/\zeta$ the equilibrium magnetisation of a ferromagnetic fluid may be written as

$$M_L(H, T, \phi) = \phi M_d\ \mathscr{L}(\zeta), \quad \zeta = \frac{mH}{k_B T} \tag{7}$$

where M_d is the bulk magnetic of the solid modified by the volume fraction ϕ and H the magnitude of the magnetic field. However, inter-particle interactions within magnetic fluids are common and the argument in the Langevin function in eq. (7) may be extended in the same way as the susceptibility in eq. (5) to