International Journal of Thermal Sciences 134 (2018) 129–139

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Infrared thermography of wall temperature distribution caused by convection of magnetic fluid

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ARTICLE INFO

Keywords:
Infrared thermography
Natural convection
Magnetic convection
Thermomagnetic convection
Magnetic fluid
In-situ calibration

ABSTRACT

Convection of a magnetic fluid within a perspex container was investigated experimentally and complemented by a computational Finite-Element model built according to the same physical specification. The enclosure was heated at two opposite side walls and exposed to a magnetic field provided by a Neodymium-Iron-Boron permanent magnet placed either above or below the container. The spatial temperature distribution on the front side wall of the container was recorded via infrared thermography (IR) and compared to computational results that reproduced the spatial temperature fields. The results show a significant effect on heat transfer by the location of the permanent magnet and gave evidence that the Kelvin body force can be much stronger than buoyancy. As both body forces are temperature sensitive an increase in temperature difference increased both, buoyancy and Kelvin body force, albeit with a different intensity that was explained via Curie's Law and expressed as a temperature dependent magnetisation through the pyromagnetic coefficient, K. The heat transfer was characterised by the Nusselt number and a suitable modified Rayleigh number that took the orientation of both buoyancy and Kelvin body force in account. The degree of heat transfer enhancement reported varied between a 23% reduction to a 20% enhancement.

1. Introduction

Convective heat transfer is a key process to provide cooling or heating to a process or component, where forced convection achieves much higher rates of heat transfer than natural convection but requires pumps or fans to provide the flow. Passive convection requires a body force induced by a temperature-dependent fluid property, such as buoyancy caused by the thermal expansion of the fluid for natural convection. Here we analyse passive convection induced by the temperature-dependent magnetisation of a magnetic fluid. A review of the manufacturing of such fluids is found in Refs. [1,2] and some of its application in Refs. [3,4].

2. Pre-existing work

A first analytical analysis of convective magnetic fluid flow was obtained by Curtis [5] in 1970 and accompanied by Lalas and Carmi [6]. Both introduced the temperature sensitive magnetisation of a magnetic fluid that may be used to induce convection based on a temperature gradient within a layer of magnetic fluid and in presence of an external magnetic field gradient when a threshold is exceeded. For this purpose a magnetic Rayleigh number was formulated that presents its empirical equivalent to the conventional Rayleigh number to quantify thermomagnetic instabilities in magnetic fluids. Since then, the literature has expanded and convection of magnetic fluids under external magnetic field gradients was studied experimentally by Sawada et al. [7] which was later complemented analytically and numerically by Snyder et al. [8] using an effective body force term that combined natural and thermomagnetic convection. The approach of Snyder's computational model approximated the external magnetic field through a constant magnetic field gradient and was able to simulate single convection cells that where either dominated by the magnetic body force or buoyancy. Realistic magnetic field distributions that conform to Maxwell's equations to induce thermomagnetic convection were studied by Ganguly et al. [9,10] using a line dipole and others [11,12]. However, the theoretical and numerical studies only considered thermomagnetic convection without the influence of terrestrial gravity which is present in many applications. For example, Früh [13] demonstrated the influence of terrestrial gravity on thermomagnetic convection in a proposed Earth-based experiment of convection in planetary interiors.

The effect of combined natural and thermomagnetic convection was

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https://doi.org/10.1016/j.ijthermalsci.2018.08.002
Received 7 February 2018; Received in revised form 2 July 2018; Accepted 1 August 2018
1290-0729/

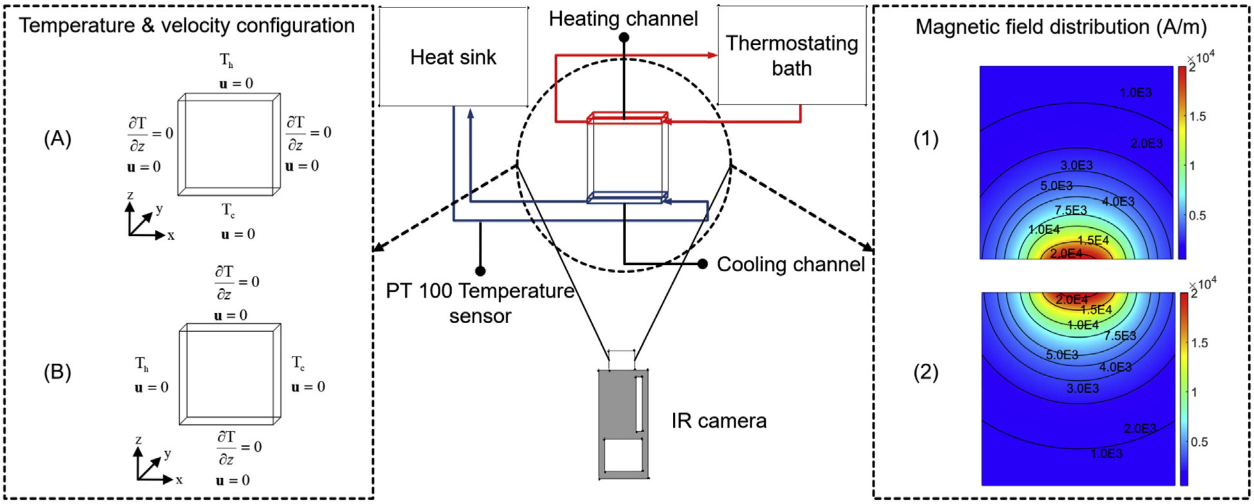

Fig. 1. Schematic of experiment (middle), with velocity and temperature configurations (left) and magnetic configurations (right) of the magnetic field, *H*, inside the cavity.

investigated experimentally and numerically by Yamaguchi et al. [14] but under the special case of a uniform external magnetic field. In that case, the leading order term in the magnetic force term vanishes and the resulting internal magnetic field gradient leading to convection is induced only by the temperature dependence of the fluid's magnetisation. Jue [15] presented a numerical analysis of the combined natural and thermomagnetic convection in a side-wall heated cavity with a magnet beneath the cavity, and therefore provides the extension of [9] to include buoyancy-induced convection. A complement, also in a numerical study, placed a magnet at the top of the square enclosure [16]. Further numerical studies have modelled combined natural and thermomagnetic convection in more complex geometries, such as C-shaped cavities [17], rectangular sections surrounding a pipe [18] or circular pipes surrounding rectangular inner sections [19]. Those simulations suggested that the spatial structure of the magnetic field and their respective orientation to buoyancy are a key factor in determining the resulting flow structure as a varying set of convection cells.

Recently, Szabo et al. [20] extended the numerical approach by Snyder et al. [8] by combining buoyancy with thermomagnetic convection induced by a realistic magnetic field from a permanent magnet for a bottom-cooled magnetic liquid with the magnet either to the side or on top of a square cavity. This was achieved by combining the solution of the magnetostatic equations and the heat and fluid equations in a single Finite-Element solver. That work provided a framework to simulate thermomagnetic convection in situations where it acts alongside terrestrial gravity. This approach was validated against experimental observations using infrared thermography as an alternative to the experimental method used by Sawada et al. [7]. They showed that magnetic forcing could overcome the stabilising effect of gravity if the main direction of the magnetic forcing was either perpendicular to gravity or parallel but opposite to gravity.

The aims of the present study is to complement the previous work Szabo and Früh [20,21]. In the general framework of the interaction between buoyancy and the Kelvin body force, there are three basic natural convection scenarios, (A) a stably stratified fluid where no convection is induced, (B) heating at a (vertical or inclined) side wall which induces a rising motion at that side wall complemented by a large-scale overturning cell in an enclosed fluid, and (C) heating at the lower surface which leads to Rayleigh-Bénard convection above a critical Rayleigh number. This can then be complemented by the Kelvin body force being largely orthogonal, parallel and acting in the same direction, or parallel but opposing. The objectives of this study was to complete the set of scenarios for the side wall heating and stably stratified cases. Rayleigh-Bénard convection is excluded from this survey as the intrinsic complexity of the regime diagram, which includes transitions to a set of global modes of convection cells and chaotic flows, prevents a clear representation of the basic underpinning effect of the interaction of buoyancy and spatially varying Kelvin body force, see e.g., [22–25].

For the remaining cases, the gravitationally stably stratified fluid subject to an orthogonal or opposing Kelvin body force were addressed numerically and experimentally previously [20]. This set is completed here with investigating the case of the Kelvin body force acting in the same direction as buoyancy. The case of sidewall heating and orthogonal Kelvin body force was investigated numerically [21] but so far only validated experimentally against a similar but not identical experiment [7]. The contribution of this study will be to provide additional direct experimental validation for the numerical results by Ref. [21], and to extend the set of buoyancy-Kelvin force configurations with side-wall heating and opposing, as well as aligned, Kelvin body force. These gaps to be filled in the set of basic interaction configurations have motivated the choice of experimental set-ups introduced in the following section.

3. Choice of experimental setup

Fig. 1 presents the schematic sketch of the experimental setup which consisted of an infrared camera FLIR T620bx with a spectral range of 7.5–14 µm at a sensitivity of 30 mK @+ 30 °C, a perspex cavity of 50 mm by 50 mm by 10 mm filled with a commercial magnetic fluid with the physical properties summarised in Table 1, a heat sink that was monitored by a PT100 temperature sensor, a temperature controlled

Table 1
Fluid properties of the experimental and numerical simulations found in Ref. [20].

Property	Symbol	Value
Characteristic length	L	50 mm
Density	ρ	1272 kg/m^3
Thermal conductivity	k	0.129 W/(m.K)
Heat capacity	c_p	1554 J/(kg.K)
Thermal expansion	β	3.85×10^{-4} K^{-2}
Dynamic viscosity	μ	2.614×10^{-2} Pa.s
Kinematic viscosity	ν	2.055×10^{-5} m^2/s
Prandtl no	Pr	316
Magnetic moment	m	2.93×10^{-25} J m/A
Volume concentration	ϕ	0.1
Bulk magnetisation	M_d	423 kA/m