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Flow transitions in a Joule-heated cavity of a low-Prandtl number fluid

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ABSTRACT

The competition of buoyancy with electromagnetic body forces is examined numerically in terms of flow structure transitions by means of a two-dimensional unsteady, finite volume model. In the present numerical study, we consider a low-Prandtl liquid metal heated by Joule effect in a rectangular cavity with an aspect ratio of 2. The direct current provides heat to the process medium by a pair of plate electrodes, located at the cavity sidewalls. The simulations have been carried out for fixed values of the Prandtl number, $Pr = 0.01$, and of the Rayleigh number, $Ra = 1.5 \times 10^4$, while the Hartmann number, Ha, varies from 0 to 10^4. The variation of Ha is found to have considerable effects on flow patterns and heat transfer inside the cavity. Several hitherto unknown flow structures are revealed, increasing in complexity with increasing Ha. Amongst the oscillatory flows predicted, intermittency and chaos are detected. The effect of Ha on the overall heat transfer performance of the system is also assessed.

1. Introduction

In this work, we examine the competition of the buoyancy force with self-induced electromagnetic body forces and their effects on heat transfer in a rectangular Joule-heated cavity, filled with a low-Prandtl number fluid of $Pr = 0.01$.

Liquid metals and molten semi-conducting materials have become key industrial materials, and a good knowledge of their characteristics of heat and momentum transfer is of great importance for the enhancement of manufacturing processes, and for delivering higher quality products. A liquid metal easily exhibits oscillatory convection, due to its low-Prandtl number. Such a phenomenon results in a decreased quality of the solidified product. Fundamental studies are expected to clarify the general mechanisms underlying unsteady convection and suggest effective ways for its control.

Application of Joule heating in engineering can be found in various industrial processes, such as electric glass melting, or the heating of molten slag in electro-slag remelters. A comprehensive review of these applications is given by Sugilal et al. [1]. The above electrothermal processes employ either direct current or low frequency, alternating currents for heating the process medium, which is generally in liquid state and placed between a pair of electrodes.

The physical phenomena taking place inside Joule-heated liquid cavities are quite complex and interrelated. Two types of body forces are present: the buoyancy force due to thermal gradients produced by volumetric Joule heating, and the Lorentz force due to the interaction between self-induced magnetic field and moving charge carriers in the liquid. The convective behavior in the liquid cavity under Joule heating depends strongly on the interaction between these forces. Depending on the Hartmann and Rayleigh numbers, the two types of driving force may either enhance or counteract each other. The non-linear interaction of the destabilizing mechanisms would result in a complicated flow structure.

Early works on low-Prandtl number convective flows have been constrained to some simplified limiting cases in which either buoyancy forces or electromagnetic body forces were present separately. To our knowledge, very few works considered the conjugated effect of electromagnetic body forces on natural convection. In this framework, in the recent works of Ozoe and co-workers [2–5], a series of experimental and numerical investigations on this topic are presented, leading to some interesting results. Sarris et al. [6], employing a numerical method, studied the unsteady two-dimensional natural convection of an electrically conductive fluid in a laterally and volumetrically heated square cavity under the influence of a magnetic field. Three-dimensional numerical simulation in cubic enclosures with both internal heat generation and an imposed uniform magnetic field was performed by Di Piazza and Ciofalo [7] to investigate the MHD free convection. In that case, the external magnetic force applied to the model, was different from the self-induced magnetic field due to the electric current.

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