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Thermal convection in a cylindrical annulus under a combined effect of the radial and vertical gravity

Antoine Meyer [a], Marcel Jongmanns [b], Martin Meier [b], Christoph Egbers [b], Innocent Mutabazi [a,*]

[a] Laboratoire "Ondes et milieux complexes", UMR 6294 CNRS – Université, Le Havre Normandie, 53, rue de Prony, BP 540, 76058 Le Havre cedex, France

[b] Department of Aerodynamics and Fluid Mechanics, Brandenburg University of Technology Cottbus-Senftenberg, Siemens-Halske-Ring 14, 03046 Cottbus, Germany

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ABSTRACT

The stability of the flow of a dielectric fluid confined in a cylindrical annulus submitted to a radial temperature gradient and a radial electric field is investigated theoretically and experimentally. The radial temperature gradient induces a vertical Archimedean buoyancy and a radial dielectrophoretic buoyancy. These two forces intervene simultaneously in the destabilization of the flow, leading to the occurrence of four types of modes depending on the relative intensity of these two buoyancies and on the fluid's properties: hydrodynamic and thermal modes that are axisymmetric and oscillatory, stationary columnar modes and electric modes which are stationary and non-axisymmetric modes. Experiments performed in a parabolic flight show the existence of non-axisymmetric modes that should be either columnar or helicoidal vortices.

1. Introduction

The alternating electric field with high enough frequency coupled with the temperature gradient gives rise to a dielectrophoretic force that can generate convective flows in a dielectric fluid [1,2]. In particular, it was that the dielectrophoretic force can be used to increase the heat transport in cylindrical systems [3,4]. The generation of convective motions by the dielectrophoretic force has been successfully tested in the GEOFLOW experiments that were performed in the Fluid Science Laboratory of the International Space Station where thermal convection patterns have been observed in a differentially rotating spherical shell submitted to a dielectrophoretic force [5,6]. Preliminary observations of the dielectrophoretic force effects in the cylindrical annulus were performed in parabolic flight experiments [7,8] where non-axisymmetric patterns were identified. The interest of the cylindrical annulus compared to spherical shells is the capacity of its implementations in the heat exchanger or in microfluidic systems. As the microgravity phase in parabolic flight experiments lasts only 22 s, it is necessary to perform an exhaustive investigation of the different effects of the control parameters of the flow systems in order to isolate the real contribution of the dielectrophoretic effect compared to the Archimedean buoyancy.

* Corresponding author.
E-mail address: innocent.mutabazi@univ-lehavre.fr (I. Mutabazi).

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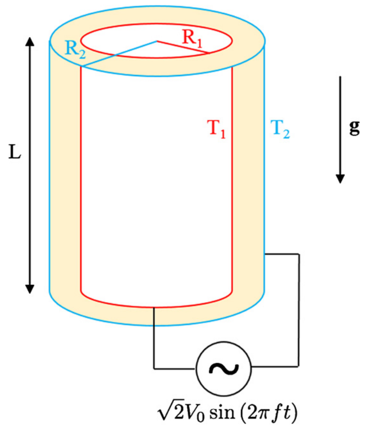

Fig. 1. Schematic sketch of the setup. The inner cylinder is heated and the voltage is applied to it. The outer cylinder is cooled and connected to the ground.

The present work presents the results of the linear stability analysis of the fluid (silicone oil) inside a cylindrical annulus with an alternating high-frequency electric field and a radial temperature gradient together with flow patterns observed during parabolic flight experiments. The paper is organized as follows: Section 2 describes the flow equations, and the results from linear stability analysis. Section 3 describes the experimental setup and the parabolic flight and presents preliminary experimental results realized in a recent parabolic flight campaign (October 2015). Discussion of the results and conclusion are addressed in sections 4 and 5.

2. Flow equations

We consider an incompressible dielectric fluid of density ρ, kinematic viscosity ν, thermal diffusivity κ and permittivity ε, confined between two concentric steady cylinders of length L and gap width d. The inner and outer cylinders of radii R_1 and $R_2 = R_1 + d$ are maintained at the temperatures T_1 and $T_2 < T_1$, respectively (Fig. 1). A high alternating electric potential is applied to the inner cylinder, while the outer one is grounded, resulting in an inhomogeneous inward directed electric field $\vec{E}$. The temperature difference between the cylinders induces the stratification in the density $\rho(T)$ and in the permittivity $\epsilon(T)$. The fluid density stratification in the Earth gravity field leads to the Archimedean buoyancy $\vec{F}_A = \delta\rho\vec{g}$, while the fluid permittivity stratification in the electric field leads to the dielectrophoretic force $\vec{F}_{\mathrm{d}} = \vec{E}^2\vec{\nabla}\epsilon$ [9]. The dielectrophoretic force dominates over the Coulomb force when the frequency of the electric field is very large compared to the inverse of the electric charge relaxation time $\tau_{\mathrm{e}} = \epsilon/\sigma_{\mathrm{e}}$, where σ_{e} is the electric conductivity [1]. In the Boussinesq approximation, all the fluid properties are assumed constant with respect to the temperature, except the density and permittivity in the Archimedean and dielectrophoretic forces, where they are assumed to vary linearly with the temperature, i.e. $\rho(T) = \rho_0[1 - \alpha(T - T_2)]$; $\varepsilon = \varepsilon_2[1 - e(T - T_2)]$, where ρ_0 and ε_2 are the density and permittivity at the reference temperature T_2.

The dielectrophoretic force can be written as follows [2]

$$\vec{F}_{\mathrm{DEP}} = \vec{\nabla}\left(\frac{\varepsilon_2 e \vec{E}^2 (T - T_2)}{2}\right) - \rho\,\alpha\,(T - T_2)\,\vec{g}_{\mathrm{e}} \tag{1}$$

The conservative term can lumped into the pressure gradient and has effects only in the case of the interface dynamics. The non-conservative term represents the dielectrophoretic buoyancy induced by the effective electric gravity field $\vec{g}_{\mathrm{e}}$ given by:

$$\vec{g}_{\mathrm{e}} = \vec{\nabla}\left(\frac{e\,\varepsilon_2\,\vec{E}^2}{2\,\alpha\,\rho}\right) \tag{2}$$

The effective electric gravity represents the gradient of the electric energy stored in the capacitor. So a fluid particle is subject to a total gravity $\vec{G} = \vec{g} + \vec{g}_{\mathrm{e}}$.

Most of the time, the frequency of the electric potential is large enough compared to the inverses of the fluid characteristic times $\tau_\nu = d^2/\nu$ and $\tau_\kappa = d^2/\kappa$ so that only the time average dielectrophoretic buoyancy can affect the fluid motion. The electric contribution reduces to that of an effective static field.

In the following, we introduce the lengthscale d, the viscous diffusion timescale τ_ν, the temperature is scaled by $T_1 - T_2$ and the electric potential is scaled by the root mean square electric potential at the outer cylinder V_0. The flow equations for the velocity field $\vec{u}$, the temperature θ, the electric potential ϕ are derived from the conservation laws of the mass, the momentum, the energy, and the charge. Written in dimensionless form, they read: