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Charge injection enhanced natural convection heat transfer in horizontal concentric annuli filled with a dielectric liquid

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ABSTRACT

The natural convection heat transfer in a highly insulating liquid contained between two horizontal concentric cylinders is shown by two-dimensional numerical simulations to be noticeably enhanced by imposing a direct current electric field. This augmentation of heat transfer is due to the radial flow motion induced by unipolar injection of ions. It is found that there exists a threshold of the electric driving parameter *T*, above which the heat transfer enhancement due to the electric effect becomes significant. For relatively small *T* values, the mean Nusselt numbers are closely related to the flow pattern and the Rayleigh number *Ra*. In addition, for sufficiently high *T* values, the flow is fully dominated by the Coulomb force, and thus the heat transfer rate no long depends on *Ra*.

1. Introduction

Electro-Thermo-Hydro-Dynamics (ETHD) is an interdisciplinary field involving complex interactions among the fluid motion, the thermal field and electrostatics [1,2]. The active augmentation of convective heat transfer by electrical forces is an important application in this field. Indeed, there are some unique advantages for heat transfer enhancement due to the electrical effects, such as the simple design, rapid and smart control of enhancement, no need of mechanical parts, low power consumption, and so on [3]. The earliest work on this subject may date back to the mid-1930s when Senftleben and Braun performed experiments of heat transfer enhancement due to the electric field in gases [4]. In the early 1950s, the first results of the influence of electric fields on convective heat transfer in dielectric liquids were reported [5,6]. Some recent experimental studies include the heat transfer augmentation using corona jets [7] and ionic winds [8], and by means of electrohydrodynamic (EHD) conduction pumping [9] and ion injection from a sharp metallic electrode in dielectric liquids [10], etc. Besides [1,3], there are several state-of-the-art reviews that cover different aspects of electrohydrodynamical enhancement of heat transfer [11–13].

In general, when a dielectric liquid is subjected to an external electric field, the electrical body force $\vec{f}_E$ arises and it may be expressed as,

$$\vec{f}_E = q\vec{E} - \frac{1}{2}E^2\nabla\varepsilon + \frac{1}{2}\nabla\left[\rho E^2\left(\frac{\partial\varepsilon}{\partial\rho}\right)_\theta\right] \tag{1}$$

where q denotes the free charge density, $\vec{E}$ the electric field, ε the dielectric permittivity, ρ the fluid density, and θ the absolute temperature. The three terms on the right-hand side of Eq. (1) represent the Coulomb force on free charges, the dielectric force and the electrostrictive force, respectively. The electrostrictive force can be incorporated into the pressure term since it can be viewed as the gradient of a scalar field, and thus it will not affect the single-phase flow [14]. The dielectric force requires a non-zero permittivity gradient, which may be achieved by imposing a temperature gradient and at the same time assuming that the permittivity is temperature-dependent [15]. However, under a direct current (DC) electric field, it is generally much weaker than the Coulomb force when there are non-negligible space charges within the liquid [14]. It should be noted that the dielectric force may become dominant (or even the only electrical body force) when an alternating current (AC) field is applied (see for example Refs. [16–20]). The Coulomb force refers to the force exerted by the electric field on the free charges present in the liquid. It is commonly the strongest electrical force when a DC field is applied [14,21].

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To better understand the mechanism of the heat transfer enhancement by EHD, it is necessary to discuss the generation of the free space charges in the flow. Various physical mechanisms have been proposed to account for the originations of free space charges. Some studies considered charges resulting from a thermally induced conductivity gradient within the liquid (see for example Refs. [22–24]). However, this model fails to explain the nonlinear current–voltage (*I*–*V*) characteristics of dielectric liquids for strong electric fields ($E > 10^4$ V/m) [14] and also the electro-convection observed in an isothermal dielectric liquid [25,26]. The dissociation–injection conductivity model that takes into account the ion injection at the liquid/electrode interface and the field-enhanced dissociation of impurities (usually salts) in the bulk is able to interpret the *I*–*V* characteristics of both highly and weakly insulting liquids for a wide range of the strength of the electric field [27–29]. When an intense electric field is applied to a highly insulating liquid, the injection of ions, which occurs at the electrical double layer due to electrochemical reactions, is considered as the main source of free charges [30]. Both theoretical analysis and experimental results have shown that the reproducible ion injections can be achieved by adding some salt into an insulating liquid [30,31]. It should be noted that though the added salt can facilitate the charge injection, it also results in a non-negligible residual conductivity.

The material presented here represents the first results of a broader research project aimed at numerically studying injection–dissociation enhanced convection heat transfer in dielectric liquids for practical applications. Previous studies based on a similar or the same physical model mainly focused on the linear instability feature of the problem [2,32]. In addition, most of these studies dealt with the simplest plate–plate configuration. From a practical point of view, the configurations of complex geometries, such as concentric and eccentric cylinders, blade/point-plate, etc., are more interesting. Two straightforward examples of application are the forced flows in pipes (wire/cylinder) [33] and fluid-filled underground electric transmission cables [34]. In this study, we consider injection as the sole source of free charges and the injection-induced secondary flows to enhance natural convection heat transfer in a horizontal concentric annulus. The present study may be viewed as an extension of our recent work on electro-thermo-convection in a planar layer of dielectric liquid [35,36]. As will be shown later, the change in geometry leads to some interesting phenomena. In another recent study [37], we numerically studied the annular electro-convection in an isothermal liquid induced by a strong unipolar injection between two coaxial cylinders, which can be viewed as the up-front work.

The remainder of this paper is organized as follows. In the next section, the physical problem is described and the mathematical model and boundary conditions are stated. Then we make a brief description of the numerical method in Section 3. In Section 4, numerical results are presented and discussed. Finally, in Section 5, we summarize our findings and point out some subsequent working directions.

2. Physical problem and mathematical formulation

The physical configuration and the two-dimensional Cartesian coordinate system (*x*, *y*) used in this work is sketched in Fig. 1. We consider an incompressible Newtonian dielectric liquid contained between two infinitely long horizontal concentric cylinders, of which the inner and outer radii are denoted by R_i and R_o, respectively. A radial DC electric field is applied across the liquid layer. The inner cylinder is kept at a constant potential $V_0(>0)$ while the outer cylinder is grounded, i.e., $V_1 = 0$. The inner and outer cylinders are maintained at uniform but different temperatures,

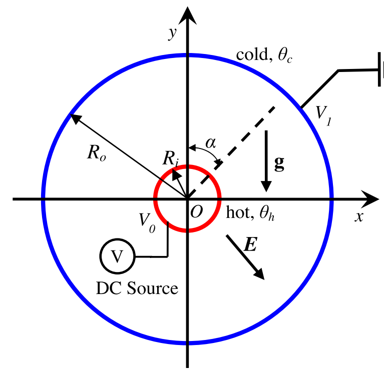

Fig. 1. A dielectric liquid layer lying between two concentric cylinder electrodes and subjected to an applied DC voltage and a thermal gradient.

θ_h and θ_c ($\theta_h > \theta_c$), respectively. The liquid is assumed to be highly insulating, and thus all free charges are from the unipolar injection-process at the inner cylinder. To further simplify the discussion, the injection is assumed to be *autonomous* and *homogeneous*. That is, the injected charge density at the emitter electrode is uniform and takes a constant value q_0. This autonomous injection can be viewed the limiting case of a general injection law proposed in [31], and it works well for a wide range of strong electric field. In addition, we assume that the charge carriers are instantaneously discharged once they arrive at the outer cylinder.

Let ρ be the density of the fluid, ν the kinematic viscosity, c_p the specific heat at constant pressure, κ the thermal diffusivity, and ε the dielectric permittivity. Under the Oberbeck–Boussinesq approximation, the flow is governed by the equation of continuity,

$$\nabla \cdot \vec{U} = 0, \tag{2}$$

the Navier–Stokes equations including the electrical force and the buoyancy force,

$$\rho_0 \left(\frac{\partial \vec{U}}{\partial t} + \vec{U} \cdot \nabla \vec{U} \right) = -\nabla p + \rho_0 \nu \nabla^2 \vec{U} + \vec{f}_E - \rho \vec{g}, \tag{3}$$

the energy equation,

$$\frac{\partial \theta}{\partial t} + \vec{U} \cdot \nabla \theta = k \nabla^2 \theta, \tag{4}$$

the charge density transport equation and Gauss' law for the electric field,

$$\nabla \cdot (\varepsilon \vec{E}) = q, \tag{5}$$

$$\vec{E} = -\nabla V, \tag{6}$$

$$\frac{\partial q}{\partial t} + \nabla \cdot (qK\vec{E} + q\vec{U} - D\nabla q) = 0, \tag{7}$$

together with the state equation for the fluid density,

$$\rho = \rho_0 [1 - \beta(\theta - \theta_0)]. \tag{8}$$

The vectors $\vec{U} = [u, v]$, $\vec{E} = [E_x, E_y]$, $\vec{g} = -g\vec{e}_y (g > 0)$ and $\vec{e}_y$ denote the fluid velocity field, electric field, gravitational acceleration, and the unit vector in the positive *y*-direction. The scalars *p*, *q*, *V* and θ stand for the dynamic pressure, charge density, electric potential and temperature. *K* denotes the ionic mobility and *D* is the charge diffusion coefficient. ρ_0 is the density defined at the reference value of temperature, θ_0 (here $\theta_0 \equiv \theta_c$). The coefficient β denotes the derivative of ρ/ρ_0 with respect to temperature.