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Study of the transition from conduction to injection in an electrohydrodynamic flow in blade-plane geometry

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A B S T R A C T

A dielectric fluid can be set into motion with the help of electric forces, mainly Coulomb force. This phenomenon, called electroconvection, can be induced by electrohydrodynamic conduction, injection, and induction. Conduction is based on the dissociation/recombination phenomenon, generates heterocharge layers, and occurs for low electric field values. Injection produces homocharge layers in the electrode vicinity and requires stronger electric fields to be initiated. This study is an experimental observation of the transition from conduction to injection of a dielectric liquid in blade-plane geometry using Particle Image Velocimetry. In addition, the electric current is measured to completely understand the flow behavior.

1. Introduction

Electroconvection is the phenomenon of setting a dielectric fluid into motion with the help of electric forces. It is used to produce electrohydrodynamic (EHD) pumps and electroconvective flows as jets, wall jets and impinging jets, etc. Several electric forces can act on a fluid to induce its motion, but Coulomb force is the most important [1]. In order to generate a Coulomb force within a liquid, a volumetric charge density or a space charge must be created. This can be achieved by three main methods: conduction, injection, and induction.

First, in conduction, the electric current is produced by positive and negative ions generated by the dissociation of molecules that come to neutralize the electrodes. Since there is no charge injection at the electrodes, electric charges produced by dissociation are attracted towards the electrode of opposite polarity. They accumulate in the vicinity of that electrode and form what is known as a heterocharge layer [2], since the polarity of this layer is different from that of its adjacent electrode. A force is produced on an electrode and is often countered by a symmetrical force of opposite sign on the second electrode. In order to obtain a fluid motion, it is necessary that the produced Coulomb force be asymmetrical on the electrode pair. This is achieved using specific electrode geometries. Conduction, generally, occurs at low values of applied electric field. Many previous studies [2–5] have theoretically, numerically, and experimentally investigated the phenomenon of conduction and its application on EHD pumps. Velocities of the order of 10 cm/s were obtained. They also obtained encouraging results for heat transfer and fluid transport applications [6] particularly in insulated applications where other EHD methods are unachievable or undesirable.

The second method is direct injection, which takes place when the electric field reaches a threshold value. It is the process of creating a space charge in the vicinity of the electrodes: electrons are injected into the liquid and bind to neutral molecules to form ions. The accumulation of electric charges results in the appearance of a non-neutral layer composed of ions having the same polarity of the electrode. This is referred to as homocharge layer. Electric charges are then repelled by the electrode. They are set into motion and, due to the fluid viscosity, drive the surrounding liquid. The fact that a dielectric liquid can be moved by ion injection has been known for over a century [7]. Several prototypes of pumps using the injection method (also called ion-drag pumps) were specially designed for cooling applications. The charge injection pressure

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generation was studied theoretically and experimentally in gases and insulating liquids [8–10]. The injection phenomenon was also studied in EHD pumps and heat transfer enhancement devices [11,12]. Velocities of the order of 1 m/s were obtained. The method has also been successfully tested on various dielectric liquids (mainly hydrocarbons). The results obtained depend on the liquid properties including viscosity and electric conductivity [13]. The injection phenomenon has been studied more than the other two methods.

In the induction phenomenon, the space charge is created by a gradient or discontinuity of the electric conductivity. In the presence of an electric field, a volumetric charge density appears in the conductivity gradient zone. This density induced charge is attracted or repelled, thus causing a motion of the liquid. Theoretical and experimental studies were carried out on EHD induction [14,15]. Experimental works have confirmed that induction can also be obtained within a liquid by using a temperature gradient to produce a conductivity gradient [16,17]. The induction process for pumping, flow control applications, and heat transfer enhancement was studied [18–21]. The behavior of induction in a condensing liquid was also studied by varying the difference of potential and the frequency of the applied electric signal [22]. The use of EHD induction appears particularly promising for heat transfer applications.

Injection is the technique that has been mostly studied. It is also the most effective. Conduction and induction, although less effective, are also promising for various industrial applications. In practice, in isothermal fluids, conduction and injection can coexist when an electric field is applied, but it is generally assumed that one phenomenon dominates the other one. All these phenomena depend on several parameters such as electrodes geometry, working fluid, operating conditions, etc.

In this paper, the transition from conduction to injection is presented. Particle Image Velocimetry (PIV) measurements are carried out on a dielectric liquid flow in blade-plane geometry. The applied voltage is increased gradually while current measurements and PIV acquisitions take place simultaneously. This geometry is used because it allows obtaining a classical flow which was commonly studied in EHD [23].

2. Experimental setup

2.1. Apparatus

A schematic diagram of the experimental apparatus is shown in Fig. 1. It consists of two copper plane electrodes (1) and (2). The dimensions of each electrode are 60 mm × 45 mm × 1 mm and their ends are rounded with a radius of curvature of 0.5 mm. The first electrode (1) is connected to a Spellman SL100 positive DC power supply providing a voltage going from 0 V up to +5 kV. It is referred to as the blade and is in a horizontal position. The second electrode (2) is grounded and is referred to as the counter-electrode in the following sections of this paper. It is placed vertically in front of the blade with an inter-electrode distance of 1 cm. These two electrodes are placed in an 80 mm × 65 mm × 40 mm cavity cell (3) made of PMMA. In order to avoid edge effects, the electrode edges are installed in two sidewalls (4) and (5) also made of PMMA. The cell is filled with the dielectric liquid through two holes (6) located on the upper surface of the cell so that air bubbles are evacuated. Two sealing strips (7) are placed in the two sidewalls to avoid leakage.

2.2. Dielectric liquid

The dielectric liquid used to conduct the experiments of this work is 3M™ Novec™ Engineered Fluid HFE-7100 whose properties at ambient temperature are presented in Table 1.

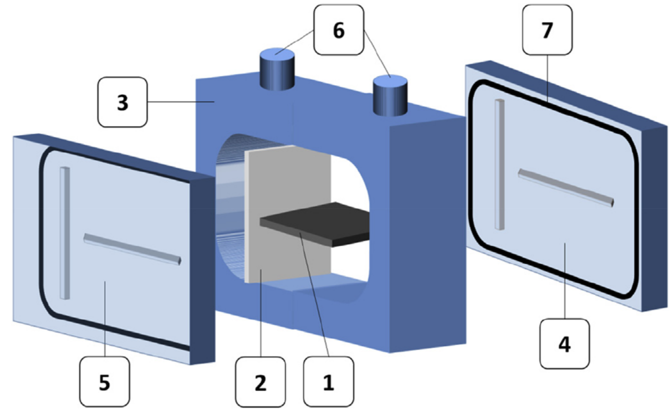

Fig. 1. Experimental apparatus.

Table 1
Properties of HFE-7100 at a temperature of 25 °C [24].

Mass density	ρ	1520 kg/m^3
Kinematic viscosity	ν	3.9×10^{-7} m^2/s
Dynamic viscosity	μ	5.9×10^{-4} Pa.s
Electric conductivity	σ	10^{-6} S/m
Dielectric strength	E_s	16 kV/mm
Relative permittivity	ε	7.4

2.3. Particle image velocimetry system

The PIV technique is a measurement method that records complete velocity fields of a desired flow configuration. A schematic is shown in Fig. 2. In this work, a LaVision PIV system (LaVision GmbH, Göttingen, Germany) was used. A Laser sheet illuminated the scene, which is seeded by very small tracer particles, and a CCD camera recorded successive images of the flow at a spatial resolution of 1376 × 1040 pixels. The software used to analyze PIV images is Davis 8.0. The velocity fields were then calculated by cross-correlation or time series with windows of 32 × 32 pixels.

2.4. Seeding particles

In order to obtain relevant PIV images, the fluid must be seeded with very small particles. Nevertheless, their concentration must not exceed a certain limit [25]. The properties of these particles must be compatible with the properties of the dielectric fluid. It must have a close mass density to avoid floatation and sedimentation along with close dielectric properties to limit particle charging. The particles used in this work are made of PTFE and have a diameter of less than 1 μm. Their properties are shown in Table 2.

3. Results

Before presenting the experimental results, a quick simulation of the applied electric field in the chamber was carried out on Ansoft Maxwell software. In Fig. 3, the electric field for a unit difference of potential between the electrodes is shown. It is evident that the highest electric field is obtained on the blade tip. That means the flow will be directed towards the tip in the case of conduction pumping and from the tip towards the counter-electrode in the case of injection pumping.