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PIV measurement and dimensionless number of electrothermally-induced fluid motion

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Abstract

This paper presents a particle image velocimetry (PIV) measurement of electrothermally-induced fluid motion and a dimensionless number to characterize the flow. An electrothermal (ET) flow is the electrokinetic motion of a fluid, generated by the simultaneous application of an AC electric field and a non-homogeneous heat source. The flow has been often used for not only transporting a fluid itself but also manipulating colloidal particles suspended in fluids. In order for such ability to be utilized in more various applications, a firm physical understanding about the ET flow should be supported. This study investigates electrothermally-induced fluid motion using PIV and based on the measured results, attempts to characterize the flow with the aid of Buckingham PI theory and parametric study. As a result of the PIV measurement, the flow vorticity was confirmed to increase proportional to the square of electric field strength, and decrease rapidly along with electrical frequencies. Also it was linearly enhanced by the gradual increase of local temperature in a fluid. These experimental measurements led to suggesting a dimensionless variable representing the ET microfluidic flow. Application of Buckingham PI theory gave the dimensionless number that consists of Coulomb force, dielectric force, and inertial force. It not only enables to predict the characteristics of ET flows driven at arbitrary conditions but also provides important insights to design and develop ET force-based micro-devices.

1 Introduction

Electrothermal (ET) flow is the electrokinetic motion of a fluid, generated by the simultaneous application of an AC electric field and a non-homogeneous heat source (González et al. (2006), Morgan and Green (2002), Ramos et al. (1998)). The heat source heats up the electrode surface biased with an AC electric field non-uniformly to induce temperature gradients in a fluid. The gradients, in turn, interact with the applied electric field to produce an ET flow by exerting electrical body force on the fluid elements. The electrical body force is expressed in a time-averaged manner, like the equation given below (Morgan and Green (2002)).

$$\langle f_e \rangle = \frac{1}{2} Re\left[\left(\frac{(\sigma\nabla\varepsilon - \varepsilon\nabla\sigma)E_0}{\sigma + i\omega\varepsilon}\right)E_0^* - \frac{1}{2}|E_0|^2\nabla\varepsilon\right] \tag{1}$$

where *Re*[ ] a real part of the bracket [ ], E a local electric field, E^* its complex conjugate, T temperature, ω (=$2\pi f$) applied angular frequency, σ and ε is electrical conductivity and permittivity of a fluid. The first and second term in the right side of Eq.(1) represents Coulomb force and dielectric force respectively, and the former dominates the latter at low AC frequencies (< 2MHz).

The ET flow received much attention from the scientific community recently because of enormous advantages that it offers. It can effectively manipulate and transport not only a fluid itself but also colloidal particles suspended in fluids in a microfluidic platform (Kwon et al. (2012), Kwon and Wereley (2015), Williams et al. (2009), Williams et al. (2008)). Such ability has been steadily applied in many research fields needing on-chip pumping and mixing of fluids, and sorting and separation of specific particles (Kwon et al. (2012), Mishra et al. (2016), Mishra et al. (2016), Mishra et al. (2016)).

However, most of the applications were achieved, depending on experience, intuition, and trial and error of researchers. If a detailed physical understanding on the ET flow is preceded, the laborious works involved in the studies can be minimized. Therefore, this study performs the flow visualization and the PIV measurement of ET fluid motion to analyze various characteristics of the flow like the following: 1) flow structure and pattern, 2) dependence on an AC frequency, an electric potential and a temperature rise in a fluid, and 3) relative contribution of natural convection in the flows. In the investigations, the ET flow is driven by placing a focused laser beam on the electrode surfaces biased with a uniform AC electric field. Based on the PIV measurement results, we construct a dimensionless number model to characterize an ET flow using Buckingham PI theory. It will help a completed understanding about physics of ET fluid motion and further, provide invaluable insights to the development of ET flow-based microdevices.

2 Experimental Setup

Figure 1 shows the experimental setup for this study. It consists of a microfluidic chip and two microscope systems. The microfluidic chip contains several chambers such as an inlet reservoir, outlet reservoir, and a microchannel. The chambers are constructed by the combination of two indium tin oxide (ITO)-coated slides of ~1mm thickness, an insulating silicone rubber sheet of ~500µm thickness, and a transparent glass cover slip of ~200µm thickness. The two ITO slides aligned in parallel in the chip serve as a pair of electrodes to supply a uniform AC electric field. The silicone sheet creates a space for generation of an ET flow by separating the two electrodes. The glass cover slip enables observing the ET flow from side-view. The detailed fabrication process of the chip is given in the reference (Kwon and Wereley (2015)).

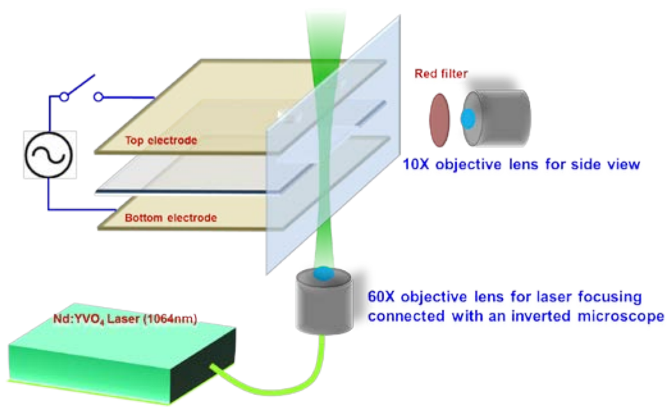

Figure 1: Experimental setup for flow visualization and PIV measurement of electrothermally-induced fluid motion.

For the driving of a light-actuated ET flow in a microchannel, the chip is mounted on an inverted microscope system operated with a function generator and near-infrared (NIR) Nd:YVO_4 laser (λ~1064nm). During experimentation, the function generator provides AC electrical signals to the ITO electrodes and the laser beam focused by an 60× objective lens induces a non-uniform temperature distribution in a fluid to produce the gradients of electrical conductivity and permittivity. Therefore, when the two driving sources are simultaneously applied to the microfluidic chip, a light-actuated ET flow is driven in the microchannel through the interaction of the electrochemical gradients and the applied AC electric field.

The ET flow is observed and visualized from side-view by a boom-stand microscope system. 3µm plain polystyrene beads are used as a tracing particle for flow visualization and PIV measurement, and are suspended in a deionized (DI) water for experiments. Their excitation and emission are achieved by a mercury-arc lamp. The emitted lights of the seed particles are captured by an interline transfer charge coupled device (CCD) camera with 7.4µm×7.4µm pixel resolution and the acquired images are analyzed by enhanced digital particle image velocimetry (EDPIV) developed by Dr. Lichuan Gui. For the PIV analysis, interrogation windows of a 64×64 pixel size are constructed and central difference image correction (CDIC) method is applied on the each image frame. The CDIC method is a cross-correlation based algorithm which is suitable for analysis of flow fields with high velocity gradients (Wereley and Gui (2003)).

3 Result and Discussion

Our visualization experiment observed that the laser-actuated ET flow takes the form of a 3D toroidal vortex. It is shown in Fig. 2(a). The applied AC signal and laser power are 20 V_{pp} at 9 kHz and 140 mW respectively. The exposure time to obtain the streamlines is 0.509 sec. When the focused laser located on the bottom electrode biased with a uniform AC electric field, the seed particles flowed in and out of the focal plane repeatedly, heading toward the optical axis (O.A.) of the applied laser beam. In other words, the particles travelled along a closed streamline, showing a source flow pattern. The presence of these closed orbits experimentally demonstrates the 3D toroidal vortex structure of the ET flow. The vortex was quantitatively analyzed by PIV technique, and it is presented in Fig. 2(b). The generated vortex shows perfectly symmetric vector and streamlines plots with respect to the origin of the polar coordinate system, i.e., r=0. Then the maximum velocity occurs at the O.A. and its value is about 95 µm/sec. The same flow pattern and velocity distribution were observed even when the laser beam was located on the top ITO electrode surface.

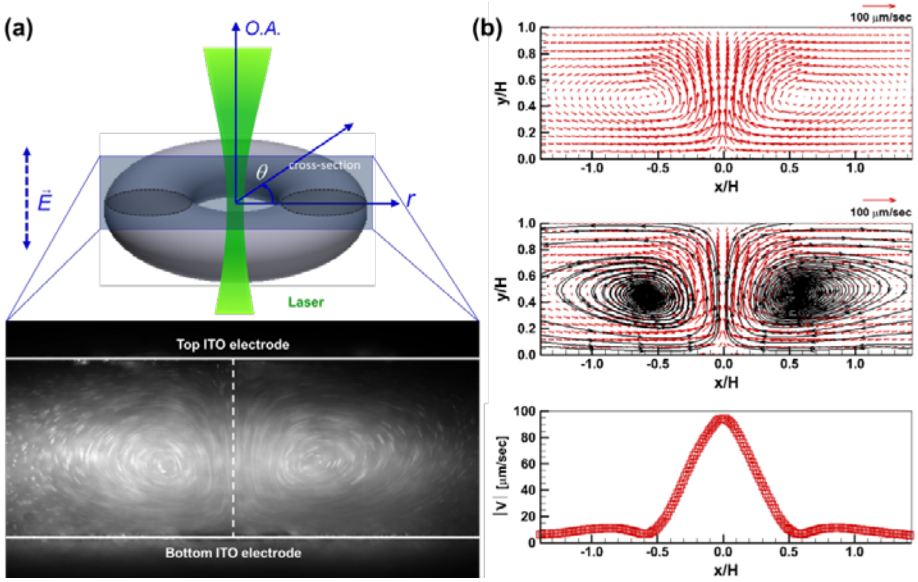

Figure 2: 3D toroidal vortex structure of a light-actuated ET flow, and its PIV analysis.

The understanding about the flow structure of the light-actuated ET microvortex led to investigation about the dependence of the vortex strength on electrical and thermal conditions. The investigation was achieved by measuring the change of the ET flow velocity with AC frequency, electric potential and temperature rise in DI water using PIV, and based on the velocity data, calculating the ET vorticities with Eq. (2) given below. The result is presented in Fig. 3.

$$\omega_\theta = [\nabla \times v]_\theta = \frac{\partial v_r}{\partial z} - \frac{\partial v_z}{\partial r} \quad (2)$$

At a constant electric field of 17.7 V_{pp} and a laser power of 90mW, the flow vorticity decreases as AC frequency increases from 100 kHz to 2 MHz. (Fig. 3(a)). This frequency-dependent change of the vorticity attributes to the dipole relaxation of the fluid molecules with the frequency increase. At a constant AC frequency of 200 kHz and a laser power of 30mW, the flow vorticity increases proportional to the square of the electric field strength (Fig. 3(b)). This phenomenon occurs because electrostatic energy stored in the fluid increases along with the increase of electric potential. At constant AC signal of 11 V_{pp} at 100 kHz, the flow vorticity increases linearly as the laser power increases from 20 to 200mW, due to the gradual change of the temperature gradient inside a fluid and its coupling effect with the applied electric field (Fig. 3(c)).

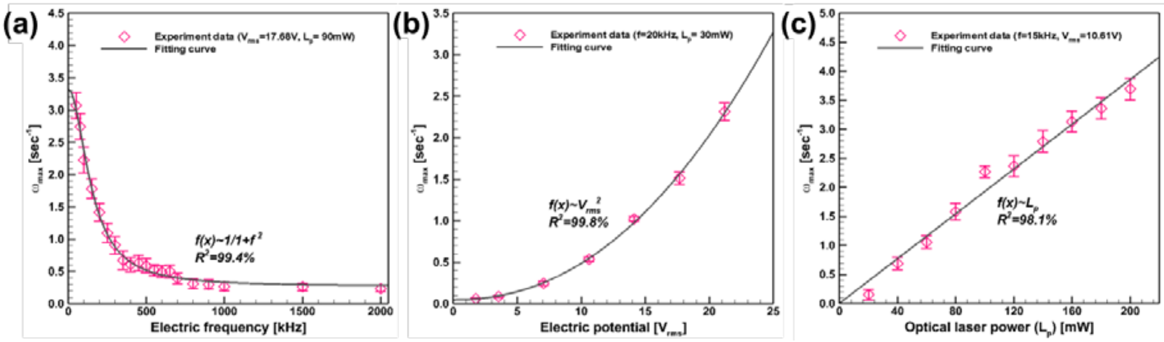

Figure 3: Dependence of electrothermally-induced fluid motion on AC frequency, electric potential, and temperature rise in a fluid.

Based on the PIV measurements, it was attempted to suggest a dimensionless number representing an ET flow using a Buckingham PI theorem. In order to identify the dimensionless number, all physical variables affecting the ET flow were selected first. Then each of the variables was converted to dimensionless form through the multiplication of the variable and the repeating variables, and the zeroization of power of the multiplied variables. It was followed by the combination and modification of the drawn dimensionless numbers. The procedure gave finally the dimensionless number of an ET flow consisting of inertial force, Coulomb force, and dielectric force. Its validity was verified by matching the dimensionless number with the PIV measurement result (Fig. 4).

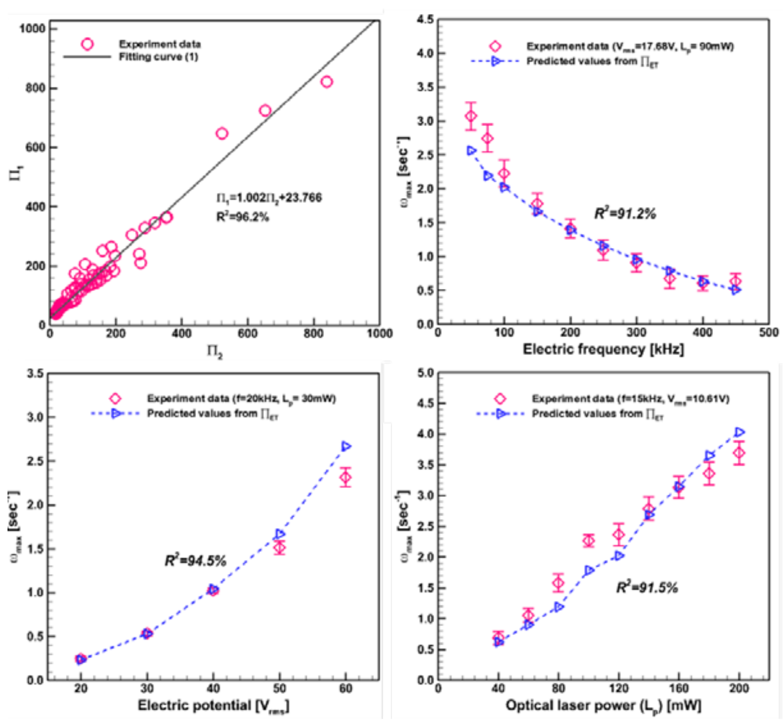

Figure 4: Dimensionless number of electrothermally-induced fluid motion, and its verification through comparison with PIV measurement data

4 Conclusion

In this paper, we performed flow visualization and PIV measurement of electrothermally-induced fluid motion and based on the result, suggested a dimensionless number representing the ET flow using Buckingham PI theorem. When a laser beam was focused on an ITO electrode biased with a uniform AC electric field, the ET flow motion was confirmed to have a 3D toroidal vortex structure. According to the PIV measurement, the gradual increase of temperature and applied electric potential caused a linear and parabolic increase of the ET vorticity, respectively. The increase of AC frequency led to a rapid decrease of the flow vorticity. Application of Buckingham PI theorem to the PIV data provided a dimensionless variable of an ET flow. The dimensionless number consisted of Coulomb force, dielectric force, and inertial force, and was in good agreement with the experimental data. The above experimental results and the theoretical model not only help a complete understanding about ET fluid motion, but also further provide invaluable insights to the development of ET flow-based microdevices.

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