MicroEHD Flow Structures under Constant Electric Fields

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Abstract—The results from studying electrohydrodynamic (EHD) vortex flows in a 1-mm gap with different geometry of electrodes and under constant external electric fields are presented. The solution of a transformer oil with iodine was used as a working fluid in which the unipolar conductivity was formed owing to the electrochemical injection of negative ions from the cathode. The EHD microvortex flow was observed using an optical microscope and snapshot with a digital video camera. The flow lines were fixed with the tracks of light-scattering microparticles 1 micron in size. The rates of flows were up to 10 cm/s at a voltage of 3 kV across the electrodes.

INTRODUCTION

Microelectrohydrodynamic flows (MEHDF) occur not only in dielectric fluids but also in aqueous and nonaqueous solutions. Therefore, to explain the development of the microEHD flows, the methods of all sorts of scientific approaches must be studied, such as physicochemical hydrodynamics, electrodynamics, and electrochemistry. The microEHD flows range from nanosizes to 1-mm sizes (Fig. 1). At present, this branch is being intensively developed, which is testified by a plurality of works published in specialized magazines, e.g., "Microfluid Nanofluid" (see review [1]).

Today, the numerical methods at a unipolar (injection) model of conductivity are extensively used to study the electrohydrodynamic (EHD) flows [2–5]. It is noteworthy that the approach like this is mainly of theoretical interest and of little practical use. High-ohmic fluids, such as dielectric, contain no double electric layers (DEL), which are always present in the aqueous electrolytes [6]. Therefore, the discharge of the ions injected on the collector has an activation character. This leads to their accumulation on the collector and, as a result, to the EHD flow decay. Since the time of discharge of the injected ions on the collector is not unlimited, the voltage in the cell had to be switched off for a few hours, which allows the EHD device's work to be restored [7]. Nevertheless, the EHD flow study in the constant fields is of interest from the scientific viewpoint for the purpose of revealing the main patterns of the electric convection development.

MicroEHD flows in the boundary EHD layers are of particular interest [8]. Thus, in the case of cooling a hot flat surface using the EHD jet, heat release occurs through the EHD boundary layer, whose thickness is fractions of a millimeter. Therefore, the injecting pin-point electrode can be located at a distance on the order of 1 mm. Hence, to develop a temperature EHD layer, a relatively low voltage can be supplied across
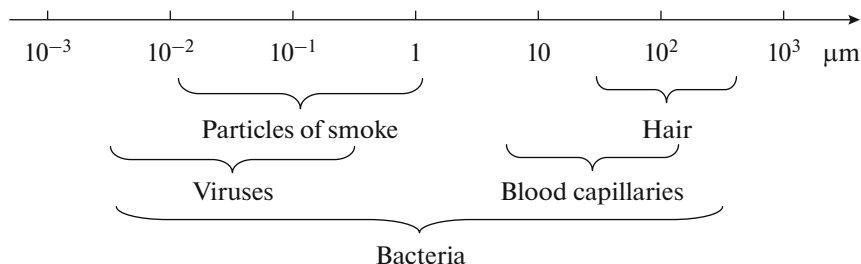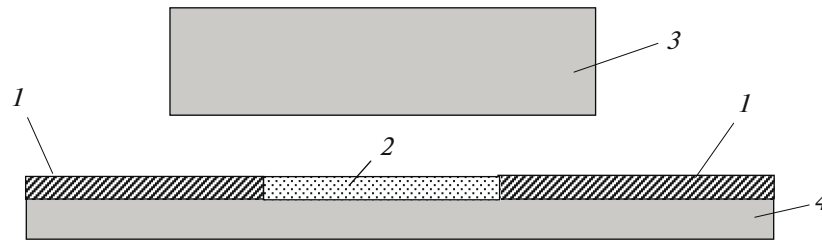

Fig. 1. Scope of microEHD flows.

Fig. 2. Scheme of the facility: (*1*) electrodes; (*2*) fluid; (*3*) microscope draw-tube; (*4*) organic glass.
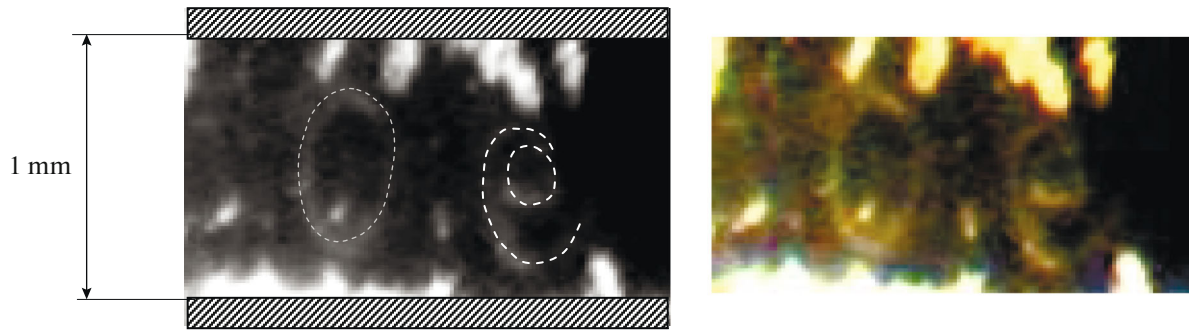

Fig. 3. Structure of microvorteces in the interelectrode gap (top view).

the electrodes, approximately 4–5 kV, which is very important technologically.

In this work, the authors describe the MEHDF structures in dielectric fluids at a maximum scale value on the order of 1 mm. The structures and dependence of the flow rates on the voltages supplied at different electrode geometries and materials of the injecting electrodes are studied.

MEHDF BETWEEN TWO BLADES

It is generally recognized at present that the EHD flows in dielectric fluids under the external constant electric fields develop owing to the injection of charges from the electrodes. This phenomenon is most typical for the asymmetric pin-plane electrode systems in nonpolar liquid dielectrics with an alloying addition. For example, the molecules of dissolved molecular iodine are electronic acceptors that amplify the injection of negative charges from the cathode [9, 10].

It is known that real electrodes are irregular, and the size of microirregularities even on the well-polished electrode surfaces is on the order of 1 μm and beyond that. Moreover, the amplification coefficients of the electric field voltage at the tips of the microirregularities can reach the values of 100 and more [11]. Hence, the microprotrusions can be the efficient injectors of charges, and the microEHD vortex flows can be formed in their vicinity. To verify this hypothesis, a study of the EHD flows was performed in the interelectrode gap, which was a thin, 1-mm wide slit between two blades (Fig. 2).

The solution of a transformer oil with iodine (TM + I) was used as a working fluid, in which, as it was aforementioned, the electrochemical injection of charges from the cathodes occurs. The microirregularities on the electrodes were created using a glue, which was used to fix the blades on the substrate made of organic glass. The experiments showed the presence of microvortices in the (TM + I) solution near the microirregularities (Fig. 3). The flow rate at a voltage of 2 kV on the electrodes can be estimated according to the tracks and time of the image exposure (Fig. 4), which is approximately 0.5 cm/s.

It is noteworthy that a similar macroEHD flow was noted in a "flat-periodically bent electrode" system [9]. As the present observation results show, similar EHD flows are detected also at the microscale sizes of the area.
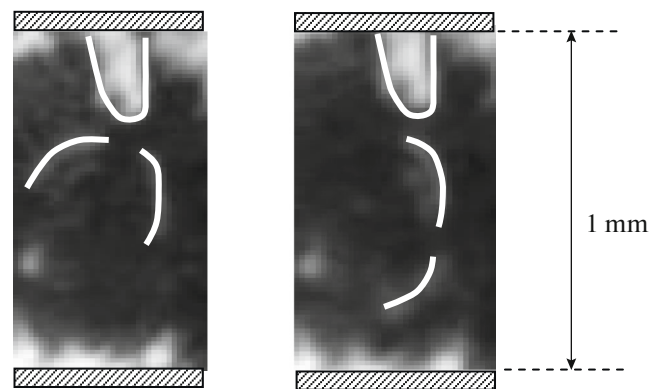

Fig. 4. Sequential images of tracks of lightscattering particles near microprotrusion. Exposure time of frame is 1/30 s.
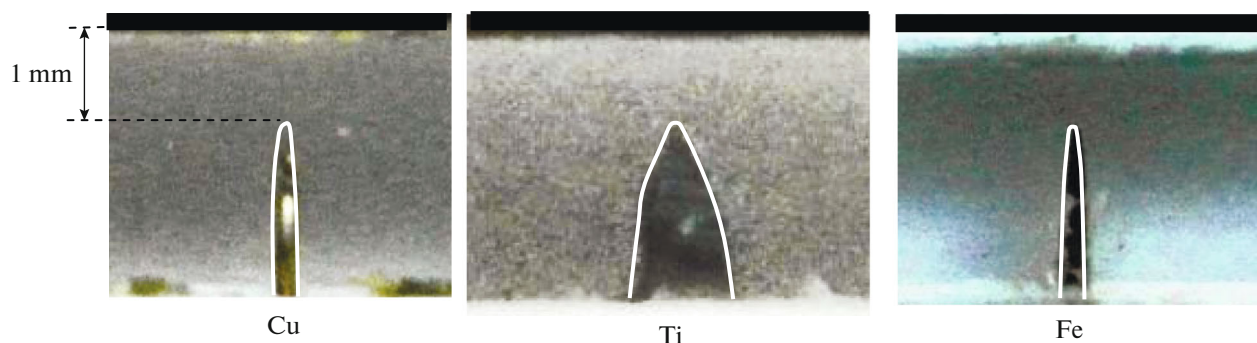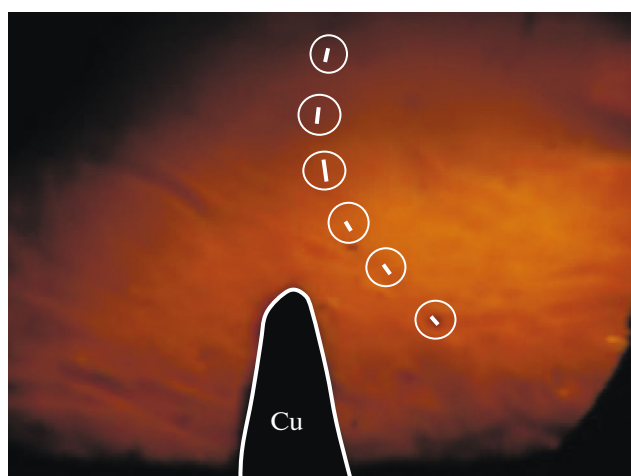
Fig. 5. Images of electrode systems.

MEHDF IN A PIN-PLANE SYSTEM

The electrode systems geometries are shown in Fig. 5. Copper (0.25-mm diameter wire), titanium, and a steel needle were used as the pinpoint electrodes. A flat counter-electrode was made of aluminum foil. A rich solution of a transformer oil with molecular iodine was the fluid to which was added small boron-silicate particles of glass with the sizes on the order of 1 μm. The pinpoint electrodes were the cathodes and flat electrodes were the anodes. The electrodes were supplied with a constant 2 kV voltage.

As in the previous experiments, the flow structure was registered using a digital high-speed camera according to the tracks of the light-scattering glass particles. The videorecording was produced using a microscope. The processing of the subsequent images allowed us to construct the lines of the current and, thus, to determine the structure of the flows. The results of the images processed at various rates of the shooting are shown in Figs. 6–8.
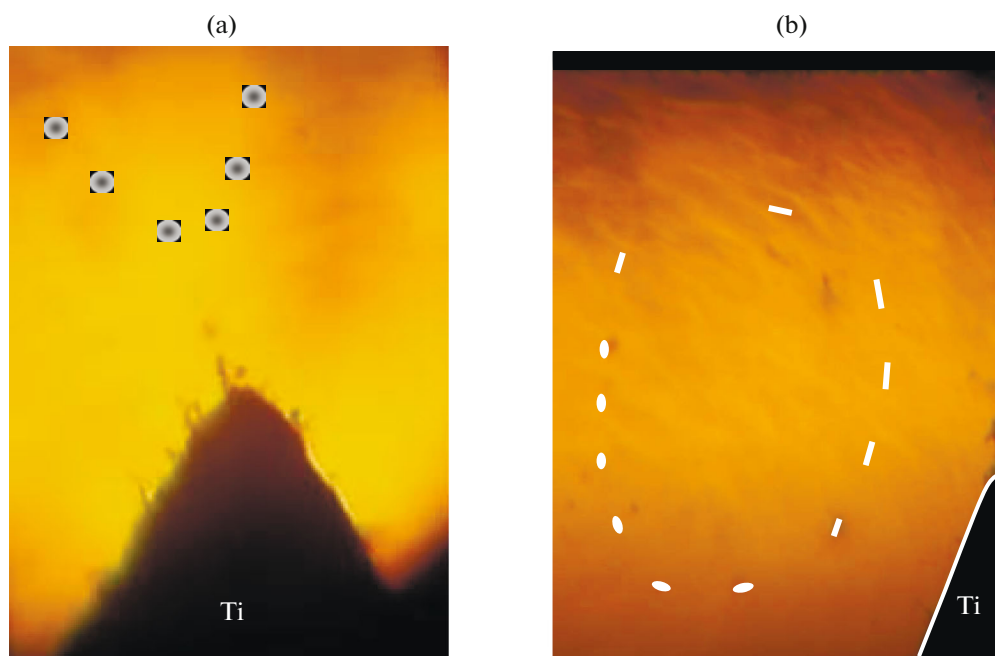

Fig. 6. Microparticle tracks near copper electrode. High-speed shooting at 240 frames per second (f/s).

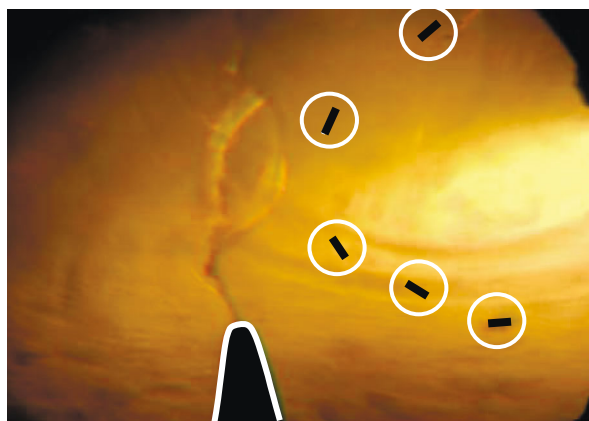**Fig. 7.** Structure of flows near titanium electrode: (a) 240; (b) 30 f/s.

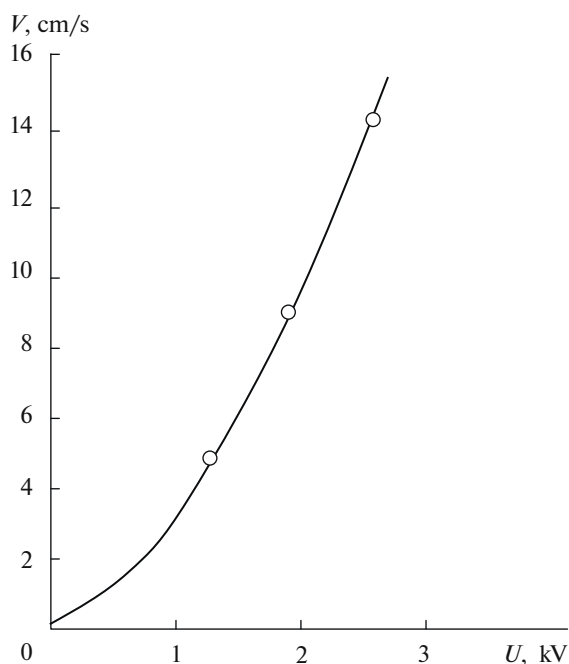**Fig. 8.** Structure of flows near steel electrode at 30 f/s.

Fig. 9. Dependence of rates in the central jet on U near the Ti electrode.

The studies showed that the flow, regardless of the pinpoint electrodes material, is directed away from the tip and has a vortex structure. At the track length of 0.1 mm and the exposure time of 1/240 s (240 f/s), the maximum rate of the flow is on the order of 2 cm/s (see the tracks in Fig. 6). Most intensively, the microparticles stick to the titanium electrode (see Fig. 7a). This results from its being highly irregular. The experiments showed as well that, in an open electrode system that contacts the air, dust particles appear in the cell with time, which short-circuits the electrodes (Fig. 8). For this reason, the electrode system must be insulated. In all cases, maximum rates of flows are observed from the tips of the pins (central jets, CJ).

The studies of particular interest are the dependences of the microEHD flow rates on the supply of voltages with a Ti pinpoint electrode (Fig. 7), since the electrode can be considered chemically inert in this case (indifferent). We can observe here only physical adsorption of the alloying addition (molecular iodine I_2), whereas, with a copper electrode, copper iodide CuI is formed on its surface [12]. Processing of the tracks of microparticles in the CJ with a Ti electrode made it possible to plot the graph of dependence of the flow rate on the supplied voltage U (Fig. 9). As is seen, the flow rate reaches of the order of 15 cm/s at 3 kV and it linearly depends on the voltage supplied in the range of 1.5−3 kV.

CONCLUSIONS

(1) The structures of the MEHDF vortex flows in the region of a 1-mm scale are similar to the EHD structures in the regions of the scale on the order of 1 cm and over it.

(2) The rates of the microEHD flows in the system of pin-plane electrodes (blade-plane) reach the values on the order of 5 mm/s at relatively low voltages of approximately 2 kV across the electrodes.

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