A Novel Geometry for a Corona Wind Electrohydrodynamic Pump

Olutosin Fawole, Massood Tabib-Azar
Electrical and Computer Engineering
University of Utah
Salt Lake City, United States
azar.m@utah.edu

Abstract—We report the flow velocity of a new electrohydrodynamic (EHD) pump configuration fabricated using a 3-D printer. It consisted of an inner conical electrode with an apex angle of 43.6 degrees and an outer conical structure with apex angles of 43.6 degrees, 63.6 degrees, 83.5 degrees, 103.5 degrees, and 180 degrees that were mounted over the inner electrode. A maximum airflow velocity of 2 m/s was measured at 8000 V/cm in the pump with the 103.5 degrees cone. In all the pumps, the velocity peaked and then dropped as the electric field reached the air's breakdown field. In these pumps, the field gradient accelerates the charged air molecules that drag the neutrons. That charged the air molecules in the inlet side of the pump which improved the efficiency.

Keywords—EHD flow; Corona Discharge; Ionic Wind; Electrohydrodynamic; 3D Printing; multiphysics modeling

I. INTRODUCTION

EHD pumps are useful for microfluidics and electronic cooling systems because they actuate the flow of fluids without moving parts. In microfluidic systems a related phenomenon using electro-osmosis is also used for pumping. In many chip-scale chemical reactors, analysis, and drug delivery systems, there is a need for efficient pumps that can generate wide ranges of flow rates (mm³/s to cm³/s) against large pressures (Δp~50 Torr).

The EHD flow problem involves a number of different physical phenomena – electrostatics, fluid dynamics, and charge transport in electric/magnetic fields (and in some cases, heat transfer). The electrostatic phenomenon is governed by the Poisson’s equation and the space charge conservation equation (equations (1-2)).

\[-\varepsilon \nabla^2 \Phi = q\]  
\[\nabla \cdot j = 0\]

\(\varepsilon\) is the permittivity, \(\Phi\) is the electric potential, \(q\) is the space charge density, and \(j\) is the current.

The fluid flow phenomenon is governed by the Navier-Stokes equations and the continuity equation for an incompressible fluid (equations (3-4)).

\[\rho u \nabla \Phi = -\nabla p + \mu \nabla^2 u - F_e\]  
\[\nabla \cdot u = 0\]

\(\rho\) is the fluid density, \(u\) is the fluid flow velocity, \(p\) is the pressure, \(\mu\) is the air dynamic viscosity, and \(F_e\) is the electrical body force.

The charge transport equation (equation (5)), couples the electrostatic and fluid flow phenomena.

\[\nabla \cdot (-D \nabla q - \mu E \nabla q) + u \cdot \nabla q = 0\]  
(5)

\(D\) is the diffusion coefficient of the charge particles, and \(\mu_E\) is the charge particle mobility.

Approximate analytical solutions exist for these equations for simple EHD pump geometry. For example, in [1], for the case of EHD pumping of a liquid between two simple parallel plate electrodes, the maximum flow velocity and volume flow rates are given by equations (6) and (7), respectively.

\[u_{max} = \frac{9 \varepsilon V^2 D^2}{8 L^3 32\eta}\]  
\[Q_{max} = \frac{9 \varepsilon V^2 \pi D^4}{8 L^3 128\eta}\]

In these equations, \(\varepsilon\) is permittivity of the liquid, \(V\) is the voltage between the plates, \(D\) is the length of the electrodes, \(L\) is the spacing between the electrodes, and \(\eta\) is the viscosity of the fluid. Furthermore, the flow velocity in a corona wind pump, where drifting corona ions collide with ambient air molecules to create a flow, is given approximately by [2]:

\[v_c = g_3 (\varepsilon/\rho g K)^{1/2} [V (V - V_3)]^{1/2}\]  
(8)

Where \(g_3\) is a function of geometry, \(\varepsilon\) is the absolute dielectric constant, \(\rho_g\) is the gas density, \(K\) is the aerodynamic loss coefficient, \(V\) is the applied voltage, and \(V_3\) is the apparent corona starting voltage. It is clear that the EHD flow rate critically depends on device geometry. The efficiency of an EHD pump is given by equation (9) [2].

\[\eta = \frac{V I}{\frac{1}{2} \rho_g A v_c^2}\]

(9)

Where \(V\) is the voltage applied between the corona electrodes, \(I\) is the corona current, and \(A\) is the cross sectional area of the duct of the flow. The efficiency of a corona wind
pump is limited because a large amount of the supplied electrical energy (95 %) goes into exciting the neutral gas molecules without moving these molecules [3]. However, the available energy for gas motion can be maximized with suitable geometry.

In addition to approximate analytical solution, there exist numerical solutions to the EHD flow problem for simple pump geometries. In [4, 5] the velocity of an EHD flow induced by a corona discharge was investigated numerically and experimentally for simple pin-plate electrode configurations. In [6], numerical methods were presented to solve the corona discharge flow, and the cooling that will result (by considering heat transfer equations in the model) from such flows. In [7,8,9], a commercial Finite Element Software (COMSOL Multiphysics) was used to model and solve the EHD flow/cooling problem. Herein, we present the experimental results of a novel geometry EHD pump, which consists of two coaxial conical electrodes. We used a 3-D printer, which enables rapid prototyping of a variety of geometries, to develop an accurate empirical model for our EHD pumps. We designed and fabricated four different EHD pumps to examine the effect of the electric field and its gradient on the EHD pumping rate. We achieved this by varying the cone angle of one the electrodes in order to optimize the maximum flow velocity achievable by the pump. We also report the efficiency of the pump. Finally, we present a simulation model using COMSOL multiphysics software that can be used to understand and optimize our pump geometry.

II. DESIGN

The EHD pumps were fabricated with a Cube 3D printer using an ABS plastic printer cartridge. The plastic was then covered with conductive tapes. The pump consisted of an inner conical electrode and an outer conical enclosure that formed the counter electrode. The pumps with different dimensions are shown in Fig. 1. The detailed part of a single pump is shown in Fig. 2. A high voltage DC converter was used to apply a high voltage between the pump electrodes. The smaller inner cone was made the positive electrode, giving a positive corona discharge. The EHD flow velocity from the positive corona discharge was measured with a hot-wire anemometer placed at the pump outlet attached to the outer cone.

Fig. 3 shows the pump flow velocity as a function of electric field strength for different outer electrodes. The outer electrode geometry with the 103.6° apex angle resulted in the largest flow velocity of 2 m/s at 8000 V/cm. Our experiments showed that high-flow EHD pumps require maximum charging to occur at the pump inlet. This requires placements of additional corona discharge electrodes at the base of the pump. Moreover, large field gradients are also required to accelerate the charged air molecules. A combination of discharge electrodes and large field gradients resulted in a high flow EHD pump. The efficiency results of the pump are given in Fig. 4 below. The pump with a 63.6° outer cone angle pumped the highest efficiency.

III. EXPERIMENTAL RESULTS

Figure 2: Schematic of the EHD pump, its inner and outer conical electrodes and its connection to the high voltage power supply.

Fig. 3: Flow rate from corona discharge conical EHD devices for different outer cone angles as a function of electric field strength. The cone angle is shown in Fig. 2.
Fig. 4: Pump efficiency for the corona discharge conical EHD devices for different outer cone angles as a function of electric field strength.

IV. SIMULATION MODEL

The simulation model, using COMSOL Multiphysics software, of the novel EHD pump geometry is given in Fig. 5 below. By solving equations (1-5) numerically in COMSOL, with appropriate initial and boundary conditions, the gas flow velocity profile, given in Fig. 6, was obtained. The surface plot shows that there are two vortices inside the pump and that the velocity at the pump output is 1 m/s at a specified electrode potential difference of 8 kV.

Fig. 5: The 2-D simulation model of the EHD pump.

Fig. 6: Surface plot of simulated surface velocity magnitude in the EHD pump. The simulated flow velocity at the pump outlet is 1 m/s. Different regions are identified in Fig. 5.

V. CONCLUSIONS

We investigated a novel geometry for a corona-discharge type EHD pump. We optimized the performance of the pump (flow velocity and efficiency) by varying one of the parameters of the pump. The experimental design and testing of different pump parameters was made easier and faster by using a 3-D printer in prototyping the pumps. We also developed a simulation model for our pump with the Multiphysics software. The combination of Multiphysics simulation and rapid prototyping with 3-D printing can lead to the design of an EHD pump with maximum performance possible.

REFERENCES