Numerical and Experimental Investigation of Flow-type Electrohydrodynamic Mixer

Albert Gazaryan, Vladimir Chirkov, Sergei Vasilkov
St. Petersburg State University, St. Petersburg, Russia
phone: (7) 911-835-05-94
e-mail: a.gazaryan@2012.spbu.ru

***Abstract*— The present study yields both the experimental and computational data on the performance of a flow-type electrohydrodynamic (EHD) mixing device with complete set of mechanical, thermal and electrophysics properties of testing liquid. The EHD mixer under study represents a channel containing high-voltage and grounded electrodes with the latter acting as a heater as well. Simulation of an actual 3D configuration is based on a new method for 3D/2D model substitution where changing time t corresponds to the displacement along the channel axis for distance z = v×t, where v is the average velocity of the external flow. The main result shows that the used computer model of EHD mixer is able to qualitatively and quantitatively estimate the performance of a realistic device with a good accuracy.**

I. Introduction

Electrohydrodynamic (EHD) systems attract the attention of many researches since late XXth century [1, 2, 3] and up to nowadays [4, 5, 6, 7]. The devices are very promising ones both for outer space and terrestrial applications owing to they provide direct electrical energy conversion into that of fluid motion, show high efficiency in meso- and micro-scale, can operate in microgravity, produce no noise, and have nearly unlimited operation life. One of the ways how heat transfer enhancement can be achieved using EHD flow (or electroconvection) is to realize liquid mixing near the hot surface, which enables heating the whole bulk of the fluid rather than just its boundary layers. This approach allows decreasing the total pressure loss thus rendering the implementation of high-power pumps unnecessary and decreasing the total power consumption of the system. Moreover, the fluid circulation in the cooling loop can be achieved also by virtue of EHD pumping, thus minimizing the electric power consumption of the whole heat exchanging system.

A major challenge of the designing EHD single-phase cooling system is the developing an effective EHD mixer that heats liquid completely in the course of pumping. The corresponding issue of fluid thermal homogenization and the disruption of the thermal boundary layer is an actual one and is discussed in a number of recent papers (e.g., [7, 8, 9, 10]). However, the complication of the underlying physics prevents the

rapid development of the EHD heat exchangers and indicates the necessity of using the computer simulation to gain more insight into the problem. In turn, the reliability of the computer model underlying the design of an EHD mixer is an open issue since existing computation techniques are still mostly unverified and fail to estimate quantitatively the performance of the corresponding devices.

In view of the above, the goal of the study is to compare computer simulation results on flow-type EHD mixing to the experimental data. The corresponding computation bases on the recently suggested techniques for the estimations of the injection function [11] and the performance of a flow-type mixing electrohydrodynamic heat exchanger [8, 9].

II. Experimental Set-Up and Procedure

In the present paragraph a description of the experimental apparatus are presented. The Fig. 1 shows an illustration of the experimental loop. The pump forces the fluid at a constant flow rate measured by flow meter with an accuracy of ±0.2 ml/s. After liquid passes the test section it cools to the desired inlet temperature in the waterlogged radiator. To simplify the filling of the closed loop the expansion vessel is presented.

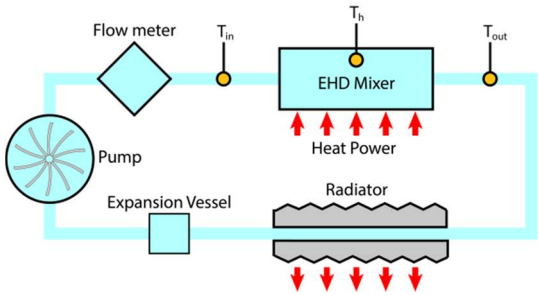

Fig. 1. Schematic of the experimental loop.

The test section is presented in Fig. 2. A cylindrical channel of 6 mm in diameter is in copper block. The bottom hole is made for the cartridge heater with controlled power input. The copper block was grounded while high voltage was applied to a system of 5 0.1 mm wires, so called wire-blade. Interelectrode gap between upper and lower wire was set to 2 mm.

The investigation is divided into two parts: pumping regime with no electric field and mixing regime when high voltage is applied. Thermoresistors measure temperatures in three points – inlet, outlet and heater.

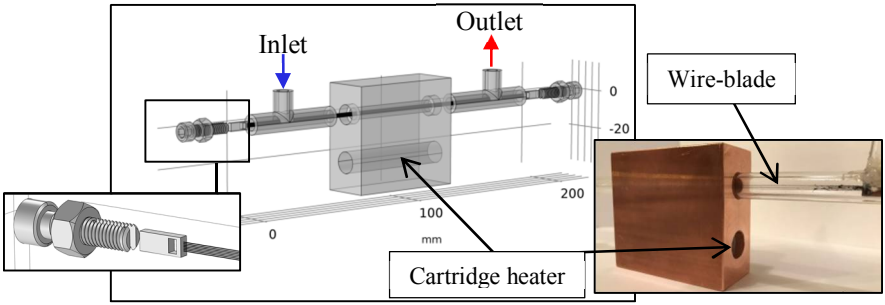

Fig. 2. Illustration and photo of the EHD mixer test section.

III. Mathematical Model and Simulation Technique

The computer simulation rests on the solution of the Nernst-Planck, Poisson and Navier-Stokes set of equations supplemented with the heat transfer one [12, 13] using COMSOL Multiphysics software package:

$$div(\boldsymbol{E}) = \rho/\varepsilon\varepsilon_0 \quad (1)$$

$$\boldsymbol{E} = -\nabla\varphi \quad (2)$$

$$\partial n_i/\partial t + div(\boldsymbol{j_i}) = g(n_1, n_2, E) \quad (3)$$

$$\boldsymbol{j_i} = n_i b_i \boldsymbol{E} - D_i \nabla n_i + n_i \boldsymbol{u} \quad (4)$$

$$\rho = e(n_1 - n_2) \quad (5)$$

$$\gamma\, \partial \boldsymbol{u}/\partial t + \gamma\, (\boldsymbol{u}, \nabla)\boldsymbol{u} = -\nabla P + \eta\, \Delta \boldsymbol{u} + \rho\, \boldsymbol{E} \quad (6)$$

$$div(\boldsymbol{u}) = 0 \quad (7)$$

$$g(n_1, n_2, E) = W_0 - \alpha_r n_1 n_2 \quad (8)$$

$$W_0 = \sigma_0^2/(e(|b_1| + |b_2|)\varepsilon\varepsilon_0) \quad (9)$$

$$\alpha_r = e(|b_1| + |b_2|)/(\varepsilon\varepsilon_0) \quad (10)$$

$$\gamma\, C_p \partial T/\partial t + div(-k\nabla T + \gamma\, C_p \boldsymbol{u} T) = 0, \quad (11)$$

where $\boldsymbol{E}$ is the electric field strength, ρ is the space charge density, φ is the electric potential, n is the ion concentration, $\boldsymbol{j}$ is the density of ion flux, $\boldsymbol{u}$ is the fluid velocity, P is the pressure, T is the temperature, ε is the relative electric permittivity, γ is the mass density, η is the dynamic viscosity, b is the ion mobility, D is the diffusion coefficient, C_p is the specific heat at constant pressure, k is the thermal conductivity coefficient, W_0 is the dissociation intensity, α_r is the recombination coefficient, ε_0 is the electric constant, k_B is the Boltzmann constant, t is the time; subscript i indicates the ion species. Upon the injection of ions into a low-conducting liquid, the system has three types of ions (those injected and two dissociated species); yet, to simplify the model and to reduce the solution time, the set involves just two kinds of monovalent ions on the assumption of the similarity of properties between injected and dissociated positive ions.

Fig. 3 presents the geometry and boundary conditions of the 2D computer model that simulates process in the cross-section right-bottom quarter of the investigating grid-plane electrode system. All parameters of the real experimental cell were very accurately measured and implemented to the model. More details on the simulation technique can be found in [11, 13, 14].

The test liquid in the present study was chosen to be Dodecane with the following properties: $\varepsilon = 2$, $\eta = 1.5\times10^{-3}$, $\gamma = 750$ kg/m^3, $\sigma_0 = 1\times10^{-11}$ S/m, $b = 1.4\times10^{-8}$ m^2/V/s, $C_p = 1650$ J/kg/K, $k = 0.14$ W/K/m. According to the Einstein relation, the diffusion coefficient of monovalent ions is $D = 3.6\times10^{-10}$ m^2/s. However, in view of the small contribution of the diffusion component to the total flow as compared to the migration and convection cones, we use an overestimated value of the diffusion coefficient ($D = 10^{-9}$ m^2/s) in the simulation to increase the stability of the numerical solution.

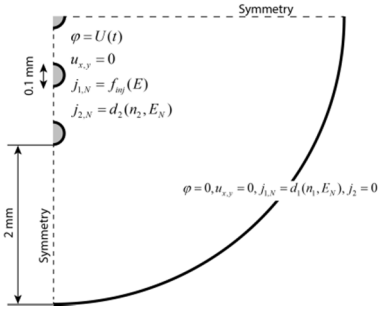

Fig. 3. Geometry of the computer model and boundary conditions.

Simulation of an actual 3D configuration is based on a new method for 3D/2D model substitution where changing time t (in the transient 2D problem statement) corresponds to the displacement along the channel axis for distance z = v×t (in 3D steady-state problem statement), where v is the average velocity of the external flow. Further details can be found in [8, 9].

IV. Results and Discussions

The present section deals with obtained results. Firstly, the dynamic current voltage characteristics (DCVCs) [15] are discussed along with temperatures measured in experiments for two regimes mentioned before. Then, the computer simulation solution is presented as well as compared to the experimental data.

A. Experimental measurements

For a constant flow rate, the removed heat power depends on the liquid heating. The more heated the coolant, the more cooled the heater. In the pumping regime, the liquid flows down the channel in a copper block and heats only due to the conduction mechanism. When the EHD mixing is on, it improves the heating by enabling the electroconvection mechanism of heat transfer. Accordingly, the results summarized in Table 1 show the temperature of the cooper block to decrease by 21.7° C.

TABLE 1: MEASUREMENTS OF THE TEMPERATURE IN SYSTEM

	T_{heater}, °C	T_{in}, °C	T_{out1}, °C	$T_{out-calc}$, °C
EHD OFF	64.8	26.5	29.6	32.8
EHD ON	43.1	27.1	30.9	33.4

Considering the energy balance on the test section, the expression $C_p \cdot \rho \cdot Q\ (T_{out1} - T_{in})$ should be 15.7 W of the input power, yet it is not so. Assuming heat losses of the test section to be negligible owing to thick thermo insulation walls and the thermoresistor measurements of the inlet temperature to be correct (as there is enough time to allow liquid temperature to become uniform over the cross-section), the only weak point of the experiment is the outlet temperature measurement. The latter fails to correspond to the average bulk temperature due to a non-uniform temperature distribution over the cross-section, which is shown hereinafter. Since the parameter is very important for further comparison with the computer model, it was decided to calculate the outlet temperature of the fluid taking into account the conservation law and the accuracy of the inlet temperature measurement. The following results are shown in column 4 of Table 1 and they are to be compared with the simulation.

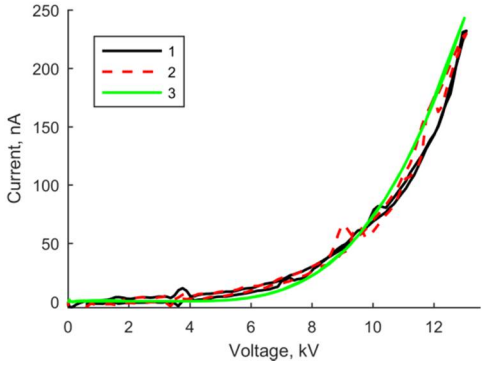

Fig. 4. Experimental DCVCs before (curve 1) and after temperature measurements (curve 2) as well as DCVC obtained in the simulation (curve 3).

One of the key problems in experimental investigation of the EHD systems is the reproducibility of the data. One should check that the system characteristics, here DCVCs, leaves unchanged for permanent conditions. Figure 4 shows the experimental current characteristics before (curve 1) and after (curve 2) temperature measurements. The negative ramp voltage up to 13 kV was applied to the wire-blade electrodes. The maximum current value attained in the system during the experiment is 235 nA at 13 kV. Curves 1 and 2 can be seen to match well, thus the system shows reproducibility and the injection function estimated by these DCVCs would describe processes in the copper block channel.

B. Simulation

Curve 3 in Fig. 4 shows the numerical DCVC obtained at the last iteration of the injection function estimation method [11]. The function has the following form:

$$f_{inj} = A\,(E - E_{st})^3\,\theta(E - E_{st}),$$

where θ is the Heaviside step function and E_{st} is the threshold value of electric field, yields a good agreement with the experimental DCVCs, when $A = 2.3\times10^{-6}$ m/(V^{3}s) and $E_{st} = 1.3\times10^{7}$ V/m.

The liquid pumps through the channel with the 2 ml/s flow rate and the average velocity 7.1 cm/s. It takes 0.7 s for the liquid to pass through the channel. This time in 2D transient problem correspond to the end of the 50 mm length channel. In the figure temperature distribution at the cross section is shown. The initial temperature of the liquid and temperature of the heater corresponds to the T_{in} and T_{heater} in Table 1 when EHD is on. Thus average outlet temperature of the liquid in the simulation is the average temperature of the Fig. 5 and is 33.5 °C.

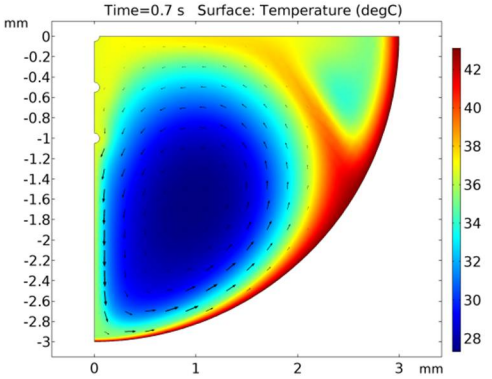

Fig. 5. Temperature distribution at the cross-section of the channel at 0.7 s, that corresponds to the end of the heater.

Comparison of the experimental and simulation data for EHD mixer shown an extremely close agreement $T_{out\text{-}cal}$ = 33.4 °C $T_{out\text{-}sim}$ = 33.5 °C. Despite such a good result the computer model need further experimental verification.

V. Conclusion

The main goal of the work was experimental verification of the EHD mixer computer model. The results include mechanical, thermal, and, which is of high importance, electrophysical measurements. Therefore, the acquired experimental data provide a sufficient base for quantitative estimation of the performance of the flow-type EHD cooling system.

Despite difficulties with the experimental set-up and unavoidable minor errors of the used numerical approaches (injection function estimation and 2D transient simulation of a 3D steady-state system), the comparison of the withdrawn heat power in the computer simulation and experiment agrees very well (with an error less than 10%). Nevertheless, the model should be slightly modified to regard the temperature dependence of the liquid and ion properties, which is likely to improve the computer model.

ACKNOWLEDGMENT

Research was carried out using resources provided by the Computer Center of SPbU and Center of Applied Aerodynamics of Research park of St. Petersburg State University.

REFERENCES

[1] B. R. Lazarenko, F. P. Grosu, and M. K. Bologa, "Convective heat-transfer enhancement by electric fields," *Int. J. Heat Mass Transf.*, vol. 18, no. 12, pp. 1433–1441, 1975.

[2] P. Atten, F. M. J. McCluskey, and A. T. Perez, "Electroconvection and its Effect on Heat Transfer," *IEEE Trans. Electr. Insul.*, vol. 23, no. 4, pp. 659–667, 1988.

[3] F. M. J. McCluskey, P. Atten, and A. T. Perez, "Heat transfer enhancement by electroconvection resulting from an injected space charge between parallel plates," *Int. J. Heat Mass Transf.*, vol. 34, no. 9, pp. 2237–2250, 1991.

[4] J. Wu, P. Traoré, M. Zhang, A. T. Pérez, and P. A. Vázquez, "Charge injection enhanced natural convection heat transfer in horizontal concentric annuli filled with a dielectric liquid," *Int. J. Heat Mass Transf.*, vol. 92, pp. 139–148, 2016.

[5] S. S. Taghavi Fadaki, N. Amanifard, H. M. Deylami, and F. Dolati, "Numerical analysis of the EHD driven flow with heat transfer in a smooth channel using multiple collectors," *Heat Mass Transf.*, vol. 53, no. 7, pp. 2445–2460, Jul. 2017.

[6] D. Testi, F. D'Ettorre, D. Della Vista, and W. Grassi, "Parabolic flight results of electrohydrodynamic heat transfer enhancement in a square duct," *Int. J. Therm. Sci.*, vol. 117, pp. 1–13, Jul. 2017.

[7] L. Yang, J. J. Barruetabena, C. D. McGuirk, L. M. Ouellette, and J. Seyed-Yagoobi, "Experimental and numerical study of fluid thermal homogenization in a spherical reservoir with EHD conduction pumping mechanism," in *2017 IEEE 19th International Conference on Dielectric Liquids (ICDL)*, 2017, pp. 1–4.

[8] A.V. Gazaryan, V.A. Chirkov, "Numerical estimation of the performance of a flow-type mixing electrohydrodynamic heat exchanger with streamlined electrode configuration," *J. Electrostat.*, unpublished.

[9] A.V. Gazaryan, V.A. Chirkov, Yu. K. Stishkov, "Numerical Estimation of the Performance of a Flow-type Electrohydrodynamic Heat Exchanger," in *2017 International Symposium on Electrohydrodynamics (ISEHD)*, 2017, pp. 1–4.

[10] F. S. Moghanlou, A. S. Khorrami, E. Esmaeilzadeh, and H. Aminfar, "Experimental study on electrohydrodynamically induced heat transfer enhancement in a minichannel," *Exp. Therm. Fluid Sci.*, vol. 59, pp. 24–31, 2014.

[11] A. Gazaryan, A. Sitnikov, V. Chirkov, and Y. Stishkov, "A Method for Estimation of Functional Dependence of Injection Charge Formation on Electric Field Strength," *IEEE Trans. Ind. Appl.*, vol. 53, no. 4, pp. 3977–3981, Jul. 2017.

[12] A. Castellanos, *Electrohydrodynamics*, Wien: Springer, 1998.

[13] V. Chirkov, E. Rodikova, and Y. Stishkov, "The Dependence of the Efficiency of Electrohydrodynamic Heat Exchanger on the Electric Conductivity of Liquid," *IEEE Trans. Ind. Appl.*, vol. 53, no. 3, pp. 2440–2445, May 2017.

[14] V. A. Chirkov, Y. K. Stishkov, and A. A. Sitnikov, "Simulation of the integral electric current characteristics of unsteady-state current passage through liquid dielectrics," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 22, no. 5, pp. 2763–2769, 2015.

[15] V. A. Chirkov, A. A. Sitnikov, and Y. K. Stishkov, "A technique for rapid diagnostics of dielectric liquids basing on their high-voltage conductivity," *J. Electrostat.*, vol. 81, pp. 48–53, 2016.