

Numerical simulation of electro-conjugate fluid flow considering electric double layer

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Abstract

An electro-conjugate fluid (ECF) is a dielectric liquid generating powerful flow when high DC voltage is applied with electrodes inserted. The ECF flow is generally known as a kind of electrohydrodynamics phenomenon. Although the ECF flow is applicable for attractive applications, its prediction by numerical simulation, which could be a powerful tool for optimum design, has been far from satisfactory. One of the plausible reasons for this failure is insufficient consideration of the electric double layer (EDL), in which positive and negative charges are stratified on the electrode surface. This study first confirms the presence of EDL by measuring the potential distribution between the symmetrical pole electrodes ($\phi 0.3$ -mm stainless steel wires) inserted in the ECF. Subsequently, the ECF flow simulation is performed by taking into account the EDL. The governing equations of ECF flow consist of a modified Poisson-Boltzmann equation, the charge conservation with charge recombination, the Korteweg-Helmholtz equation, the continuity equation and the incompressible Navier-Stokes equation. These governing equations give the distribution of potential, electric field, charge density and flow velocity as a result of numerical computations. We demonstrate that by properly considering the EDL the numerical simulation can reasonably well reproduce the ECF flow in terms of the velocity distribution and the induced flow rate.

Key words : Functional fluid, Electro-conjugate fluid, Electrohydrodynamics, Numerical simulation, Electric double layer

1. Introduction

An electro-conjugate fluid (ECF) is a kind of dielectric liquid which generates a flow (ECF flow) when high DC voltage is applied with a tiny electrode pair. A typical example of the ECF flow generation is shown in Fig. 1. In this example, a needle-ring electrode pair with high DC voltage applied is inserted in the ECF, and the ECF flow is generated from the needle tip to the bore of ring. This kind of phenomenon is generally called electrohydrodynamics (EHD) phenomenon. Yokota, et al. (2000) found a necessary condition for dielectric liquids under which strong flows are induced and defined the liquids satisfying that condition as the ECF.

Flow characteristics of the ECF have been experimentally studied so far, and it is known that the flow has higher power with smaller electrode pairs with the same input voltage. This means that the ECF flow is suitable as a tiny hydraulic power source (Yokota, et al., 2000). We can find attractive applications of the ECF flow such as a micro artificial muscle actuator (Takemura, et al., 2007), a liquid cooling system for electronic chip (Yokota, et al., 2005), a droplet transportation system for micro total analysis system (μ TAS) (Abe, et al., 2013), a liquid rate gyroscope (Takemura, et al., 2009). While impressive, their performances highly depend on the ability of ECF flow generation.

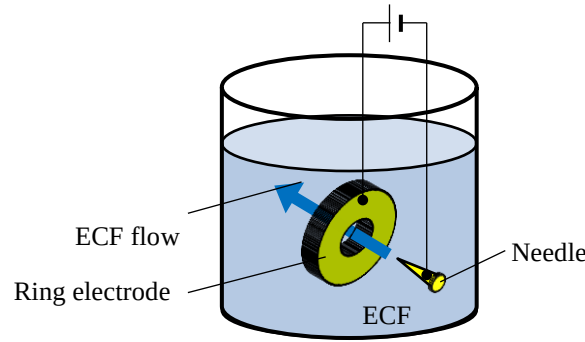


Fig. 1 Schematic of the ECF flow generation with a needle-ring electrode pair.

This means that an optimization of the electrodes pair configuration is highly required, which is so far designed by trials and errors. Such a design process is obviously costly and time-consuming.

To put the design process more sophisticated, several flow simulations for the ECF flow generations have been reported in recent years. Yanada, et al. (2010) introduced the ion drag pump mechanism (Stuetzer, 1960) to numerically reproduce the flow of dibutyl sebacate (DBS), which belongs to the ECF family, which was experimentally observed using a triangular prism and slit electrodes pair. Hosoda, et al. (2013) performed a numerical analysis of the flow generated in the FF-1EHA2 (New Technology Management Co., Ltd.), which also belongs to the ECF family, with a symmetrical pole electrodes pair. Despite these efforts, numerical simulations still fail to reasonably reproduce the experimental data. For instance, the pressure and flow rate reproduced in the flow simulation by Yanada, et al. are not corresponding quantitatively to the experimental data. The flow velocity distribution obtained by the computation by Hosoda, et al. is qualitatively similar to the experimental data; however, the flow velocity distribution around the electrodes was quantitatively different from that observed in the experiment.

One of the plausible reasons for these failures must be insufficient consideration of an electric double layer (EDL), which quite often appears near the electrode surface where the electric potential is applied. Therefore, this study aims to numerically reproduce the ECF flow by properly taking into account the EDL that has not been considered in previous studies. First, we confirm the presence of EDL in the ECF by measuring the potential distribution between electrodes. Subsequently, we perform an ECF flow simulation taking into account the EDL, and compare the computed and measured flow velocity distributions.

Nomenclature

a	limiting distance between two solved ions [m]
D^+	diffusion coefficient of cations [m^2/s]
D^-	diffusion coefficient of anions [m^2/s]
e	elementary charge [C]
E	electric field [V/m]
E_{static}	electrostatic field strength [V/m]
E_{thres}	threshold electric field strength [V/m]
Fv	body force [N/m^3]
j	current density [A/m^2]
k^+	proportional constant for injected cations density [$\text{C}/(\text{V} \cdot \text{m}^2)$]
k^-	proportional constant for injected anions density [$\text{C}/(\text{V} \cdot \text{m}^2)$]
k_B	Boltzmann's constant [J/K]
K_G^+	geometrical shape factor of cations [–]
K_G^-	geometrical shape factor of anions [–]
L_x	position electrons are peeling [m]
n	wall-normal coordinate [m]
n_0	ion number density [$1/\text{m}^3$]

p	pressure [Pa]
q	ion density [C/m^3]
q^+	cation density [C/m^3]
q^-	anion density [C/m^3]
q_e^+	injected cation [C/m^3]
q_e^-	injected anion [C/m^3]
r^+	cation radius [m]
r^-	anion radius [m]
T	temperature of a dielectric liquid [K]
t	time [s]
$\mathbf{u}$	flow velocity [m/s]
u_x	flow velocity of the x direction [m/s]
u_y	flow velocity of the y direction [m/s]
V_{app}	applied voltage [V]
z	ion number [-]
Δt	time step [s]
ε_0	dielectric constant of vacuum [F/m]
ε_r	dielectric constant [-]
η	viscosity [$Pa \cdot s$]
μ_{IW}^+	mobility of cations calculated by Walden's rule [$m^2 / (V \cdot s)$]
μ_{IW}^-	mobility of anions calculated by Walden's rule [$m^2 / (V \cdot s)$]
μ_I^+	mobility of cations [$m^2 / (V \cdot s)$]
μ_I^-	mobility of anions [$m^2 / (V \cdot s)$]
ν	kinematic viscosity [m^2 / s]
ρ	density of fluid [kg/m^3]
ϕ	voltage [V]
ϕ_{thres}	threshold electric potential [V]

2. Measurement of electric double layer

2.1 Generation of electric double layer

When an electric potential is applied to a dielectric liquid, an electric field is generated between electrodes. If there exist any anions/cations in the liquid, the anions and cations travel due to the Coulomb force toward the positive and negative electrodes, respectively. Consequently, these ions are arranged in layers near the electrodes surfaces (schematically illustrated in Fig. 2). These layers are called the electric double layer (EDL). In the presence of the EDL, the potential distribution between the electrodes becomes non-linear, which affects the electric field as well. Since the ECF is generally a dielectric liquid, the EDL may be present in the ECF. We will confirm the presence of the EDL in the ECF in this section.

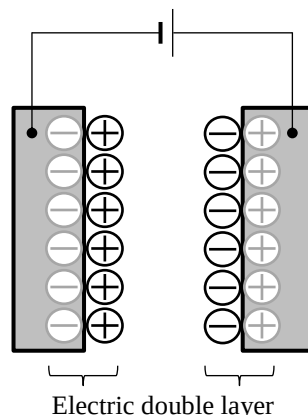


Fig. 2 Schematic of the EDL.

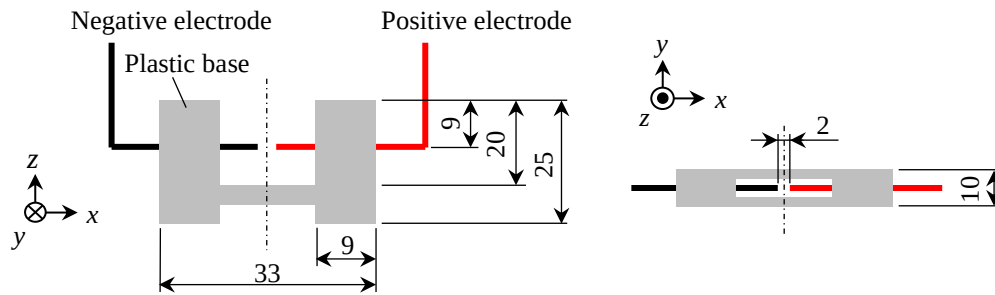


Fig. 3 Symmetrical pole electrode pair. Negative/positive electrodes with diameter of 0.3 mm are coaxially aligned with 2-mm gap.

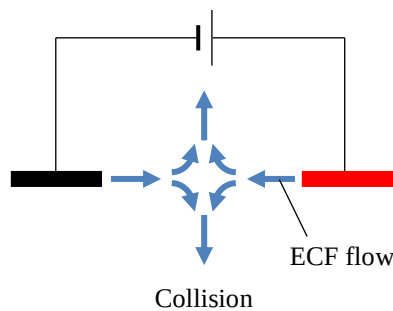


Fig. 4 Schematic of the ECF flow generation with a symmetrical pole electrodes pair. The ECF flow is generated from the tip of each electrode, and colliding at the center region.

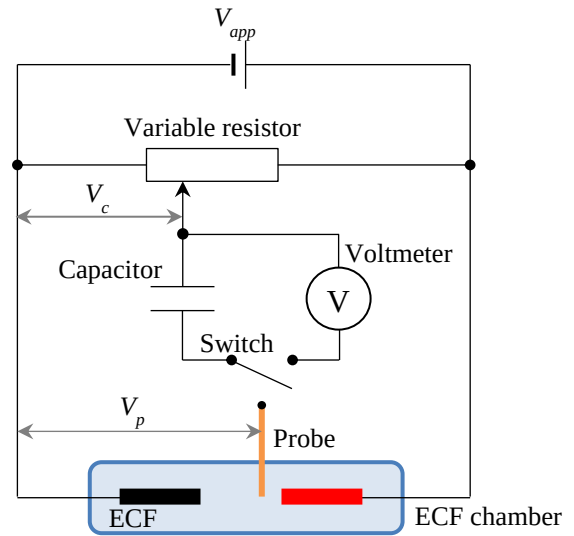


Fig. 5 Experimental setup and circuit configuration for potential measurement.

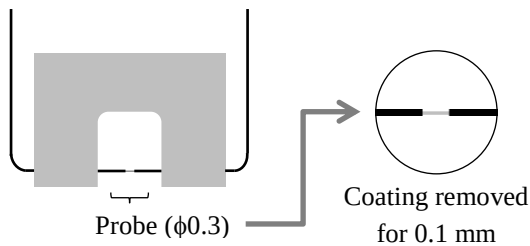


Fig. 6 A probe used for potential measurement.

Table 1 Physical properties of FF-1EHA2.

Relative permittivity	5.2
Conductivity [S/m]	4.5×10^{-8}
Density [kg/m ³]	1688
Viscosity [mPa·s]	7

2.2 Setup and procedure

This study uses a symmetrical pole electrodes pair (Mori, et al., 2011; Hosoda, et al., 2013) shown in Fig. 3 in order to generate the ECF flow. The working fluid used is FF-1EHA2 (New Technology Management Co., Ltd.), which belongs to the ECF family, whose physical properties are shown in Table 1. With these electrodes configuration and working fluid, it is known that a colliding jet is observed between the electrodes as shown in Fig. 4 (Mori, et al., 2011; Hosoda, et al., 2013). The diameter of pole electrodes is 0.3 mm, and the electrodes are coaxially aligned using a plastic base with the interelectrode gap of 2 mm.

In order to confirm the presence of the EDL near the electrodes while applying the voltage to the ECF via the aforementioned electrode pair, we measured the potential distribution between the electrodes by using the electrostatic probe method (Yatsuzuka, et al., 1982). An experimental setup and a circuit configuration are shown in Fig. 5. A probe, which is used for the measurement of potential, is shown in Fig. 6. The probe is composed of a $\phi 0.3$ mm copper wire

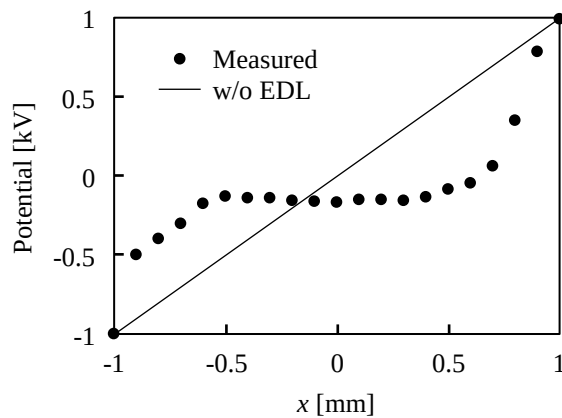


Fig. 7 Measurement result of potential distribution.

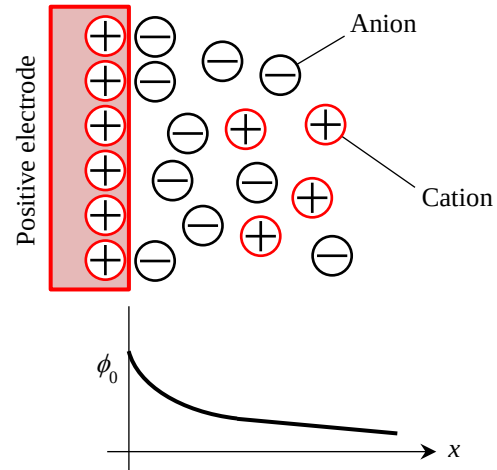


Fig. 8 Schematic of the CG model expressing the EDL.

with insulating coating, however, the coating is removed at its center for 0.1 mm. The probe is inserted from above to the electrodes interspace, and the 0.1-mm long bare copper wire is placed just in between the electrodes. In order to measure the potential distribution between the electrodes, an ECF chamber is moved along the x -axis by using a positioning stage by every 0.1 mm interval. The applied voltage to the electrodes pair is 2 kV, which is high enough to generate the ECF flow.

The potential at each measuring position can be acquired by the following procedure. First, we connect the switch to the probe side to charge up the capacitor as,

$$Q = CV = C(V_p - V_c) \quad (1)$$

where, C represents the capacitance of capacitor, V_p and V_c represent the potential difference between the probe/GND and the variable resistor/GND, respectively. Once it becomes $V_p = V_c$ by adjusting the variable resistor, no charges are charged up to the capacitor. This can be confirmed by connecting the switch to the voltmeter side, i.e., the voltmeter becomes irresponsive when the switch is connected to the voltmeter side in case of $V_p = V_c$. Then, the potential of probe V_p can be obtained as,

$$V_c = \frac{R_c}{R} V_{app} \quad (2)$$

where, R represents the resistance maximum of the variable resistor, and R_c is the corresponding resistance of the variable resistor to the case of $V_p = V_c$.

2.3 Result of measurement

The experimental result for the potential distribution measurement is shown in Fig. 7. Here, the potential along x -axis, which is the axis common to the pole electrodes, is plotted. Steep gradients are observed near the electrodes, i.e., at around $x = -1$ mm and 1 mm, while the potential is nearly constant in the center region between the electrodes. In the absence of EDL, the potential must linearly increase, as shown with the solid line in Fig. 7, from the negative electrode to the positive one. Thus, we can conclude that the EDL cannot be neglected in the ECF.

3. Mathematical models

3.1 Model of electric double layer

Several models of the EDL have been reported such as Helmholtz model, Gouy-Chapman (GC) model and Stern model (Moore, 1974). Among them, this study adopts the GC model shown in Fig. 8 because this model is widely used in the EDL studies (Borukhov, et al., 1997). The potential distribution in the CG model in general is expressed as

$$\nabla^2 \phi = \frac{2ze n_0}{\epsilon_0 \epsilon_r} \sinh\left(\frac{ze\phi}{k_B T}\right) \quad (3)$$

with the Poisson Boltzmann equation (Moore, 1974). However, it is known that the potential distribution in a dielectric liquid under the high DC voltage is expressed as

$$\nabla^2 \phi = \frac{q}{\varepsilon_0 \varepsilon_r} + \frac{z e n_0}{\varepsilon_0 \varepsilon_r} \frac{2 \sinh(z e \phi / k_B T)}{1 + 4 a^3 n_0 \sinh^2(z e \phi / 2 k_B T)} \quad (4)$$

with the modified Poisson Boltzmann equation (Borukhov, et al., 1997).

3.2 Governing equations for ECF flow

Once the potential is given by Eq. (4), the electric field $\mathbf{E}$ can be obtained as

$$\mathbf{E} = -\nabla \phi. \quad (5)$$

Note that the electric field is instantly determined compared with the transient response of ECF flow, so that we neglect the time dependency of the electric field. Then, the body force $\mathbf{F}_v$ in the dielectric liquid, when subjected to a high DC voltage, is expressed as

$$\mathbf{F}_v = q\mathbf{E} - \frac{\varepsilon_0}{2} E^2 \nabla \varepsilon_r + \frac{\varepsilon_0}{2} \nabla \left(E^2 \frac{d\varepsilon_r}{d\rho} \rho \right) \quad (6)$$

with the Korteweg-Helmholtz equation (Panofsky, et al., 1967). The first term in the right-hand side of Eq. (6) represents the Coulomb force acting on charges, which are injected from the electrodes surfaces. The second term represents the force induced by a non-uniform dielectric liquid whose dielectric constant is the function of electric field. The third term represents the electrical strain force acting on the dipole. However, the second term can be ignored because the ECF is generally composed of a single material, meaning that the dielectric constant in the ECF is always constant. The third term can also be ignored because the ECF is an incompressible liquid, meaning that the dielectric constant does not vary. Therefore, the force acting on the ECF can be considered as the Coulomb force only. Thus, the body force $\mathbf{F}_v$ in the ECF can be simply expressed as,

$$\mathbf{F}_v = q\mathbf{E}. \quad (7)$$

Considering the body force $\mathbf{F}_v$, the governing equations for the ECF flow can be expressed using the incompressible Navier-Stokes equation and the continuity equation, i.e.,

$$\frac{\partial \mathbf{u}}{\partial t} = -(\mathbf{u} \cdot \nabla) \mathbf{u} - \frac{1}{\rho} \nabla p + \nu \nabla^2 \mathbf{u} + \frac{q\mathbf{E}}{\rho}, \quad (8)$$

$$\nabla \cdot \mathbf{u} = 0. \quad (9)$$

Moreover, the transport equations for the ions are also required. The ions existing in a dielectric liquid are driven by the electric field, the flow of liquid, and the thermal diffusion (Stuetzer, 1960). Therefore, the transport equation of ions is expressed as

$$\frac{\partial q^\pm}{\partial t} = -\nabla \cdot \mathbf{j}, \quad (\mathbf{j} = q^\pm \mu_i^\pm \mathbf{E} + q^\pm \mathbf{u} - D^\pm \nabla q^\pm). \quad (10)$$

However, since the diffusion coefficient D is generally very small according to our order evaluation, Eq. (10) can reduce to

$$\frac{\partial q^\pm}{\partial t} = -\nabla \cdot \mathbf{j}, \quad (\mathbf{j} = q^\pm \mu_i^\pm \mathbf{E} + q^\pm \mathbf{u}). \quad (11)$$

The ion mobility $\mu_i^\pm$, which appears in Eq. (11), is computed by the Walden rule (Inuishi, et al., 2007), i.e.,

$$\mu_{iw}^\pm \eta = \pm \frac{e}{6\pi K_G^\pm r^\pm}. \quad (12)$$

The right-hand side of Eq. (12) is theoretically constant (Inuishi, et al., 2007). According to the experiments by Adamczewski, et al. (1969), the constants with liquid hydrocarbon are $\mu_{iw}^+ \eta = 2.0 \times 10^{-11} \text{ A} \cdot \text{s} / \text{m}$ and $\mu_{iw}^- \eta = -3.0 \times 10^{-11} \text{ A} \cdot \text{s} / \text{m}$.

Therefore, once the viscosity is known, the ion mobility $\mu_i^\pm$ in the liquid can be obtained by the Walden rule. As a

result, using the physical properties shown in Table 1, the mobility of anion and cation of FF-1EHA2 can be calculated as $\mu_{nw}^- = -0.429 \times 10^{-8} \text{ m}^2 / (\text{V} \cdot \text{s})$ and $\mu_{nw}^+ = 0.286 \times 10^{-8} \text{ m}^2 / (\text{V} \cdot \text{s})$, respectively. However, Inuishi, et al. (2007) reported that the Walden rule would possibly underestimate the ion mobility under the high voltage applied because the rule is derived under the assumption that an ion loses its momentum by a single collision with a neutral molecule. Thus, in the present study, we determined as $\mu_I^\pm = 50 \times \mu_{nw}^\pm$, with which the calculated result agrees with the experimental data.

We also consider the charge injection from the electrode surfaces. According to the previous report by Yanada, et al. (2010), charges are injected when the electric field at the electrode surface exceeds a threshold value. This charge injection is expressed as,

$$q_e^\pm = k^\pm (E_{\text{static}} - E_{\text{thres}}) \quad (13)$$

where, E_{thres} is the electric field of the electrode surface when the ECF flow starts to generate. The threshold potential ϕ_{thres} , which is corresponding to E_{thres} , is previously measured with FF-1EHA2 to be 212.5 V (Hosoda, et al., 2013).

Finally, we consider a recoupling of anions and cations to become neutral molecules when they collide each other. In addition, according to our experimental observations, it is reasonable to consider that an electron emitted from the negative electrode peels from an anion at a certain distance, defined as L_x , away from the electrode. In other words, the anion becomes a neutral molecule when it travels for the distance, L_x , from the electrode tip. Together with the recoupling of anions and cations, this assumption is expressed as,

$$q = q^+ + q^-, \quad (14)$$

$$q^- = 0 \quad (x > L_x). \quad (15)$$

Equation (15) is a quite phenomenological expression; however, this is introduced as a simple expression for the relaxation effect of ions.

3.3 Numerical computation methods and conditions

The computational domain and the domain focused on are shown in Fig. 9. The governing equations are discretized by using a staggered grid system. The grid is uniform in both directions and the number of grid points is 100 in each direction. We have verified that use of larger number of grids than 100×100 does not affect the result of numerical simulation. The boundary condition at each boundary (numbered from 1 to 8) is shown in Fig. 9, and is expressed as

$$\begin{aligned} \boxed{1} : \phi &= -\frac{V_{\text{app}}}{2}, \quad \frac{\partial q^+}{\partial x} = 0, \quad q^- = q_e^-, \quad \mathbf{u} = 0, \quad \frac{1}{\rho} \frac{\partial p}{\partial x} = \nu \frac{\partial^2 u_x}{\partial x^2}. \\ \boxed{2} : \phi &= \frac{V_{\text{app}}}{2}, \quad q^+ = q_e^+, \quad \frac{\partial q^-}{\partial x} = 0, \quad \mathbf{u} = 0, \quad \frac{1}{\rho} \frac{\partial p}{\partial x} = \nu \frac{\partial^2 u_x}{\partial x^2}. \\ \boxed{3} : \phi &= -\frac{V_{\text{app}}}{2}, \quad \frac{\partial q^\pm}{\partial y} = 0, \quad \mathbf{u} = 0, \quad \frac{1}{\rho} \frac{\partial p}{\partial y} = \nu \frac{\partial^2 u_y}{\partial y^2}. \\ \boxed{4} : \phi &= \frac{V_{\text{app}}}{2}, \quad \frac{\partial q^\pm}{\partial y} = 0, \quad \mathbf{u} = 0, \quad \frac{1}{\rho} \frac{\partial p}{\partial y} = \nu \frac{\partial^2 u_y}{\partial y^2}. \\ \boxed{5} \ \boxed{6} \ \boxed{7} \ \boxed{8} : \frac{\partial \phi}{\partial n} &= 0, \quad \frac{\partial q^\pm}{\partial n} = 0, \quad \frac{\partial \mathbf{u}}{\partial n} = 0, \quad \frac{\partial p}{\partial n} = 0. \end{aligned}$$

The procedure for the ECF flow simulation is as follows. First, the potential distribution ϕ and the electric field $\mathbf{E}$ are calculated by Eqs. (4) and (5). Second, the ion density q is calculated by Eqs. (11), (13), (14), and (15). Finally, the flow velocity $\mathbf{u}$ is calculated with Eqs. (8) and (9). The successive over-relaxation (SOR) method is used to solve Eq. (4), the constrained interpolation profile (CIP) method is used to solve Eq. (11), and the simplified marker and cell (SMAC) method and third order Runge-Kutta method are used to solve Eq. (8). Also, the bi-conjugate gradient stabilization (Bi-CGSTAB) method is used to solve the Poisson equation of the pressure in the SMAC method. In this study, we conduct the computation until 2.5 s after the step input of voltage is applied to the electrodes pair.

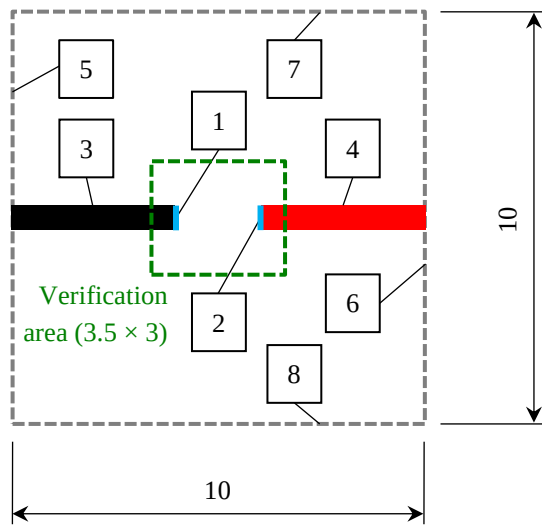


Fig. 9 Computation domain and verification area.

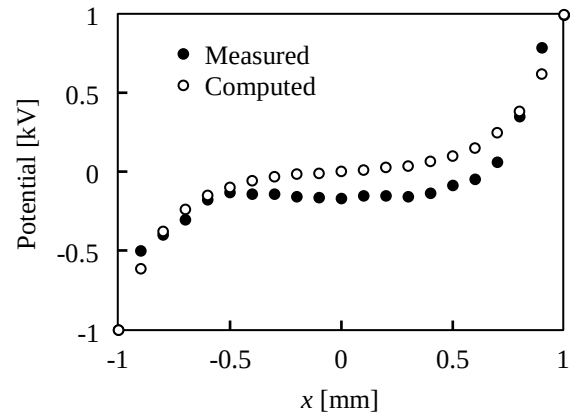


Fig. 10 Measured and computed potential distribution.

Table 2 Constants used in the numerical simulation.

a [m]	1.0×10^{-8}	ε_0 [F/m]	8.85×10^{-12}	μ_t^+ [m ² /(V·s)]	1.430×10^{-7}
Δt [s]	1.0×10^{-4}	ε_r	5.2	μ_t^- [m ² /(V·s)]	-2.145×10^{-7}
k^+ [C/(V·m ²)]	4.0×10^{-9}	ϕ_{thres} [V]	212.5	n_0 [m ⁻³]	4.0×10^{17}
k^- [C/(V·m ²)]	-6.0×10^{-9}	η [Pa·s]	7.0×10^{-3}	T [K]	298.15
L_x [mm]	0.3	ρ [kg/m ³]	1,688		

The parameters used in the numerical simulation are shown in Table 2. However, the unknown parameters, $k^\pm$, L_x and n_0 , are determined by trials and errors so as to fit the experimental results.

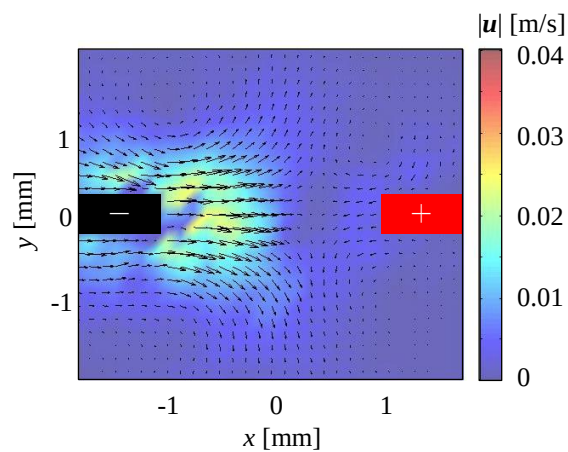
4. Computation results and discussion

4.1 Effect of electric double layer

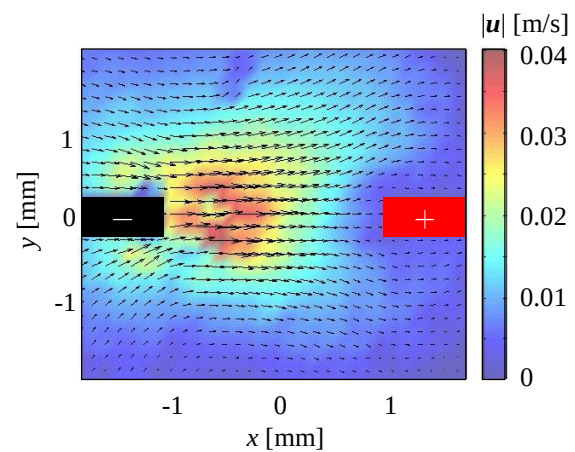
An important contribution of this study is the introduction of the GC model in the ECF flow simulation. In order to validate whether the GC model is reasonable or not, the computed potential is compared with the experimental result as shown in Fig. 10. The figure shows that both the computed and experimental potentials have steep gradients near the electrodes. It is also shown that both potentials are nearly constant in the center region between the electrodes. In addition, the computed potential quantitatively agrees with the experimental data. From these features, we can conclude that the GC model is suitable for representing the EDL in the ECF.

4.2 Induced ECF flow

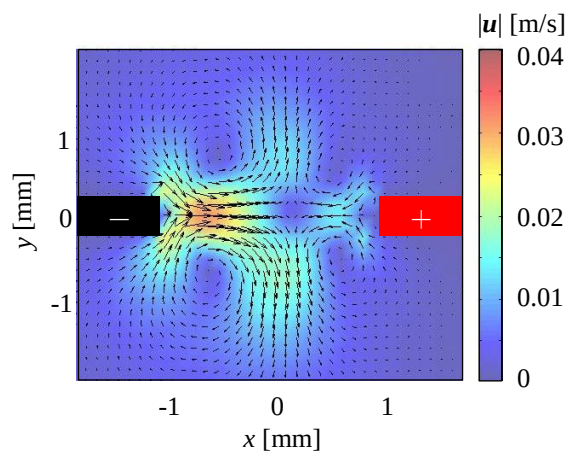
Flow velocity distributions of the induced ECF flows at $t = 0.05$ s and 2.5 s are shown in Figs. 11 and 12, respectively: (a) is the experimental result by Hosoda, et al. (2013), (b) is the computed result with taking into account the EDL, and (c) is the computed result without taking into account the EDL. Vectors in these figures represent the flow velocity $\mathbf{u}$, and the color contour represents their magnitudes. In Figs. 11 and 12, stronger jets are observed from the negative electrode than from the positive electrode. This may be due to the dominant charge polarity in the ECF. According to our experimental study (Mori, et al., 2011), more negative charges are injected from the negative electrode than positive charges from the positive electrode. This means that the dominant charge polarity is negative when we apply voltage to the ECF. According to this fact, k^+ and k^- are set by trials and errors as in Table 2, in order to make the jet on the negative electrode side stronger. At the time instant shortly after the voltage is imposed (Fig. 11), all the flow velocity distributions have similar features as follows. The ECF flows are induced from both electrodes, and



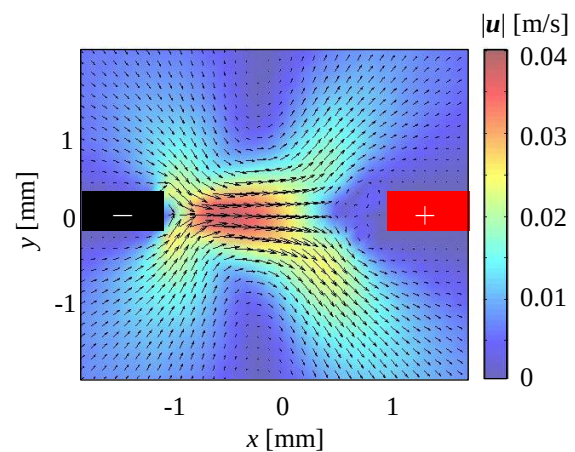
(a) Experimental result



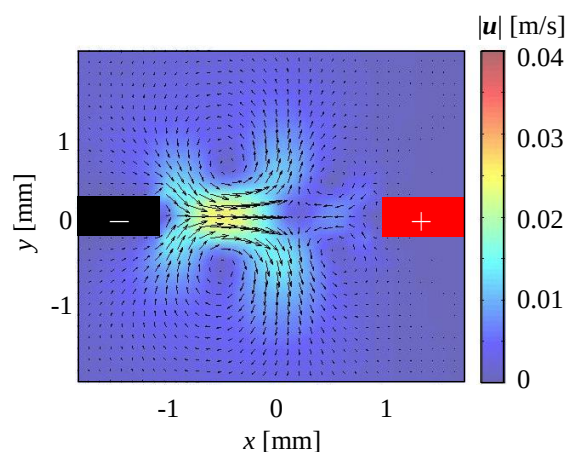
(a) Experimental result



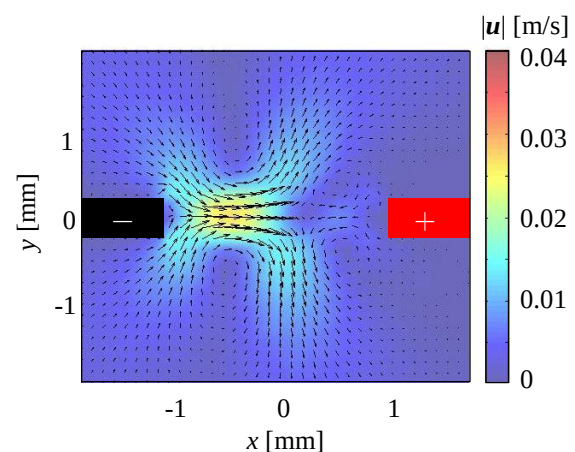
(b) Computed result w/ EDL



(b) Computed result w/ EDL



(c) Computed result w/o EDL



(c) Computed result w/o EDL

Fig. 11 Flow velocity distribution at $t = 0.05$ s.

Fig. 12 Flow velocity distribution at $t = 2.5$ s.

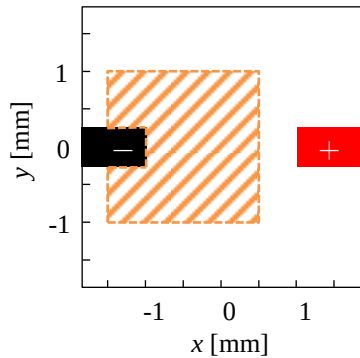


Fig. 13 Verification area for the averaged flow velocity.

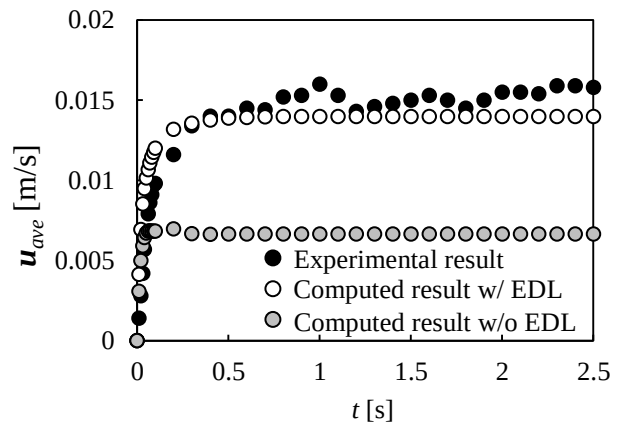


Fig. 14 Time history of averaged flow velocity.

they collide at the interspace of the electrodes. The positions of the collision are located at a little closer to the positive electrode. This means a stronger flow is induced from the negative electrode compared to the positive side. In addition, four vortices near the edges of electrodes can be observed in all figures. On the other hand, in the cases of the fully-developed flows (Fig. 12), the features of the flow velocity distributions are slightly different, i.e., the experimental result and the computed result taking into account the EDL (Figs. 12a and b) have different features compared with Figs. 11a and b, while the flow velocity distribution without taking into account the EDL (Fig. 12c) does not have any significant difference compared with Fig. 11c. In Figs. 12a and b, the flow induced from the positive electrode is suppressed because the dominant charge polarity is negative in the ECF as mentioned above and the negative charges are strongly accelerated by the strong electric field generated by the EDL. In addition, the recoupling and peeling defined in Eqs. (14) and (15) might affect this suppression; accordingly, the vortices near the positive electrode disappear. This may also trigger the expansion of the region near the negative electrode, where the relatively higher flow velocity is observed. This high flow velocity is likely generated by the steep gradient of the electric field due to the EDL near the electrode.

In order to quantitatively compare these three results, the time history of the averaged flow velocity within the $2 \times 2 \text{ mm}^2$ area near the negative electrode (Fig. 13) is shown in Fig. 14. As can be seen, the experimental data and the computed result taking into account the EDL are in good agreement, while the computed result without taking into account the EDL significantly underestimates the experimental data. From these, we can conclude that consideration of the EDL model is essential in the ECF flow simulation.

5. Conclusion

This study introduced the GC model, which expresses the EDL, to the flow simulation of ECF. From the comparison of the results of experiment and the computations with and without taking into account the EDL, we found the quantitative adequacy for the introduction of the GC model, at least in case of the flow generation with symmetrical pole electrodes pair and FF-1EHA2. We should confirm in our future study the generality of this conclusion with different electrode configurations and different working fluids in the ECF family.

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