Importance, Challenges and Solution of EWOD Platform for droplet Actuation and Mixing

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Abstract: Advancement in micro-fabrication processes has led the concept of Electrowetting on dielectric (EWOD), one of the ideal paradigm for lab-on-a-chip systems based upon micromanipulation of discrete droplets. It enables control over fluid shape and flow by electrical signals alone, which is viable by effective utilization of the excess charge accumulation at the interface between the droplet and the dielectric surface, also by polarization of line tension at the three-phase line.

EWOD helps in discretizing the flow and hence it is called as Digital microfluidic (DMF). DMF technology offers a platform for Lab-on-a-chip (LoC), which is concerned with the design of micro total analysis system (µTAS) for chemical and biological applications with the advantages of portability, higher sensitivity, reagent volume reduction, faster analysis, increased automation, low power consumption, compatibility with mass manufacturing, and high throughput. This emerging technology combines electronics with biology to open new application areas such as point-of-care diagnosis, on-chip DNA analysis, and automated drug discovery.

In this paper, we efforts to address the challenges with DMF system to enhance the system performance and also for transporting and merging application, using multiphase simulation modules of COMSOL Multiphysics. 2-D arrangement of all-in-single plane employed for simulation, resultant with ±0.2 deviation of anticipated result.

Keywords: Lab-on-a-chip, Digital microfluidics, Contact angle, Electrowetting, Electrowetting on dielectric (EWOD), COMSOL Multiphysics.

I. INTRODUCTION

Recent year a great deal of scientific research is being committed to automate, integrate and miniature microfluidic devices [1], [2], so that, it can be widely applicable and accessible. Various techniques such as thermocapillary [21] electrocapillarity [8] electro-osmosis [9], acoustics [10], electric forces [11], electromagnetic [12], electrophoresis [13], electrocapillary/electrowetting [22]–[25]) have been reported to advance the microfluidic devices, but among all EWOD is unique, because it is a direct way of controlling the surface tension of a fluid [17]. However Lab-on-chip (LoC) is such a device capable of handling a complete chemical or biological analysis protocol. One of the most prominent lines of research to attain this target consists in manipulating discrete volumes of fluids called droplets rather than forcing continuous phase flow, thus microfluidic based on electrowetting is often referred to as digital microfluidics [2]-[6].

II. IMPORTANCE AND CHALLENGES

It has been reported by Center for Drug Research that, “The development of new pharmaceuticals is extremely expensive and time consuming. It takes an average of 13 years and more than 1 billion USD to develop a new drug. The single biggest factor driving this cost is the rate of failure, which about 90% of drug discovery project failing in the late clinical phases of development” [14]. Also the Research in the field of chemistry, biology and medicine (clinical and drug delivery) are lagging where the hundreds of reaction parallel need to take place simultaneously. These are the challenges that researchers are facing currently.

The challenges with EWOD devices are the deciding threshold voltage, used for clinical diagnostic to protect the cell from damage [15], avoiding the cross talk between electrodes because of electrostatic effect to maintain droplet on proper track and the automated multiplexing technique use for switching the electrode voltage.

III. THEORY

While voltage switch from current electrode to adjacent electrode, shape of the droplet will deformed and concurrently will follow the electrical path of the switching, this mechanism is called EWOD.

A. The Principle of EWOD

Lippmann proposed that by applying external voltage across the capillary, an electrostatic field will be generated and because of electrostatic charge interfacial tension between liquid-gas and liquid-substrate will changed [16], eventually resulting in deformation of a liquid droplet (Figure 1(a)), This phenomenon of droplet deformation due to change in contact angle effected by applied voltage is referred to as electrowetting on dielectric (EWOD). In our previous work we illustrated the change in contact angle with

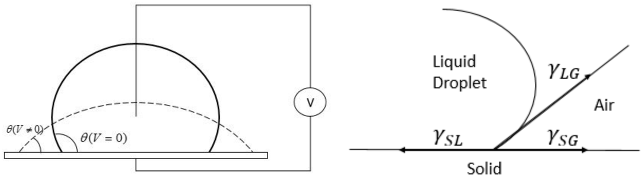

Figure 1. (a) Electrowetting Principle. (b) Three phase interphase line of solid, liquid and gas.

respect to change in voltage [31]. Here we have continued and demonstrations the modulation efficiency plot with relative change in contact angle Vs voltage.

B. Droplet Deformation

When a potential is applied, an electric field will generate (because of excess charge accumulation at three phase line tension [14]-[17], [25] or polarization of dielectric layer [7]), which lead the change in interfacial tension or surface tension between the liquid-gas and liquid-solid, resulting as change in contact angle or droplet deformation. The solid-liquid interfacial tension (γ_{SL}) (Figure 1(b)) can be controlled by the electrical potential across the interface, and the result is expressed by using the Lippmann's Eq. (1) [16]

$$\gamma_{SL}(V) = \gamma_{SL}(0) - \tfrac{1}{2}CV^2 \qquad (1)$$

Where C (F/m2) is the capacitance of the dielectric layer, V is the applied voltage and $\gamma_{SL}(0)$ is the solid-liquid interfacial tension at potential zero.

The contact angle (θ) of droplet at the interface of dielectric layer can be measure by Young's Eq. (2) [19]

$$\cos\theta = (\gamma_{SG} - \gamma_{SL}) / \gamma_{LG} \qquad (2)$$

Where γ_{SG} and γ_{SL} are the interfacial tension of solid-gas and liquid-gas respectively. Incorporating the Young's Eq. to the Lippmann's Eq. (3), the resulting the change in contact angle $\theta(V)$ due to applied potential (V), and hence called Lippmann-Young equation

$$\cos\theta(V) = \cos\theta(0) + \tfrac{\varepsilon_0\varepsilon}{2\gamma_{LG}d}V^2 \qquad (3)$$

Here, $\theta(V)$ is the resting contact angle i.e. without any applied potential. ε (8.85×10-12F/m) is the permittivity of the free space, ε is the dielectric constant of dielectric layer, and d is the thickness of the dielectric film. Note that γ_{SG} and γ_{LG} assumed to be constant i.e. independent of applied potential [20].

C. Droplet Transport

A droplet can be transported by switching the voltage from current electrode to adjacent electrode, this cause asymmetrical change in the three phase line tension. No matter which method use for changing the interfacial tension (e.g., Electrocapillarity [8] Electro-osmosis [9], Acoustics [10], Electric forces [11], Electromagnetic [12], Electrophoresis [13] Thermocapillary [21] or Electrocapillary/Electrowetting[22]–[25]), the asymmetrical change in the interfacial tension induces an asymmetrical deformation of the liquid meniscus, which establishes a pressure difference inside liquid, gives a bulk fluid movement [26], which can be predicts using Brochard's model Eq. (4) [22], [27].

$$U = \frac{\varepsilon_0\varepsilon(1-\cos\theta(V))}{6\mu dl\sin\theta(V)}V^2 \qquad (4)$$

Where μ and l are the viscosity of the droplet and an empirical factor respectively.

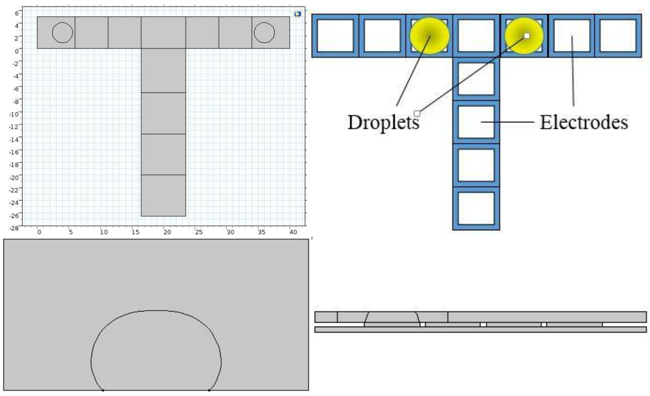

Figure 2. (a- top right) Mixing platform in comsol (b- top left) Diagramatic view (c- bottom right) change in contact angle platform in comsol (d- bottom left) On track or Mistrack testing platform in comsol.

IV. IMPLEMENTATION IN COMSOL MULTIPHYSICS

In this section, we discuss geometry design, Fluidic flow pattern and Boundary condition, COMSOL Physics used for simulation and electrode addressing.

A. Geometry design of EWOD chips

The principal of various fluidic-operation is droplet manipulation. Although various geometry with driving factor has been proposed [28], [29]. The EWOD chips have much more attention because of portability, higher sensitivity, reagent volume reduction, faster analysis, increased automation, low power consumption, compatibility with mass manufacturing, and high throughput [25], [30] and also for direct way of controlling the surface tension of a fluid [17]. Figure 2(b) represent the schematic view of the EWOD platform. 'T' shape platform (Figure 2(a)) is designed for testing and simulation of droplet transport and mixing. The simulation for change in contact angle has been carried out on Figure 2(c) platform whereas Figure 2(d) geometry has used for finding the saturation voltage. The principle of Lippmann-Young equation and Brochard's model has been implemented to deformation and transportation respectively. The width and length of the electrodes are 5µm and 5.5µm respectively for 1-6 electrodes, for 8-11 electrodes it is 6.7µm and 7µm respectively and for 7 it is 5µm and 7µm respectively. The different size of electrodes are chosen as the fluid volume is different at different time and places.

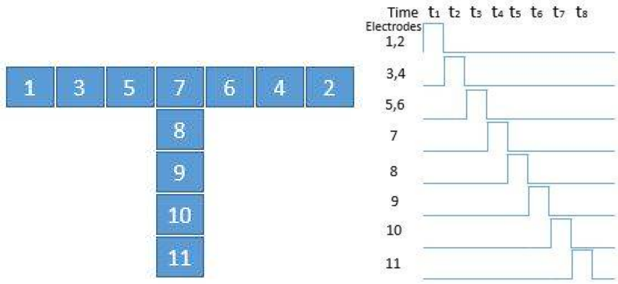

Figure 3. Diaramatic view of electrodes swetching

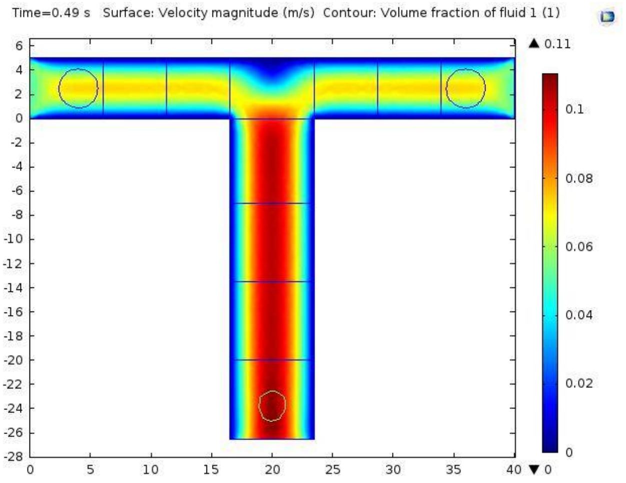

Figure 4. Velocity profile of the droplet

B. *Fluidic flow pattern and Boundary condition*

Assuming fluid flow as Incompressible flow and also neglecting the inertial term (stokes flow), the Navier–Stokes equation can be expressed as Eq. 5 where, U is the fluid velocity, ρ is the fluid density, p is the pressure, μ is the dynamic viscosity, F is the represents body forces per unit volume and ∇ is the vector operator

$$\rho \frac{\partial U}{\partial t} + \rho (U \cdot \nabla) U = -\nabla p + \mu \nabla^2 U + F$$
$$\nabla \cdot U = 0 \quad (5)$$

Convection Diffusion equation has been used for mixing two different concentrated fluid. The droplets have the concentration 0 and 1 mol/m^3 respectively.

$$d_a \frac{\partial con}{\partial t} + \nabla \cdot (-c \nabla con) + \beta \cdot \nabla con = f$$
$$\nabla = [\tfrac{\partial}{\partial x}, \tfrac{\partial}{\partial y}] \quad (6)$$

Where d_a is the damping coefficient, β is the convection coefficient, c is the diffusion coefficient, and con is the concentration, f is the source term. All the values of coefficient are one.

The liquid-air interface can be defined for time dependent solution as Eq. (7)

$$u_1 = u_{2,} n_1 \cdot T_1 = \sigma (\nabla_t \cdot n_1) n_1 - \nabla_t \sigma$$
$$u_1 = u_2 + M_f (\tfrac{1}{\rho_1} + \tfrac{1}{\rho_2}) n_1 \quad (7)$$
$$u_{mesh} = (u_1 \cdot n_1) - \frac{M_f}{\rho_1} n_1$$

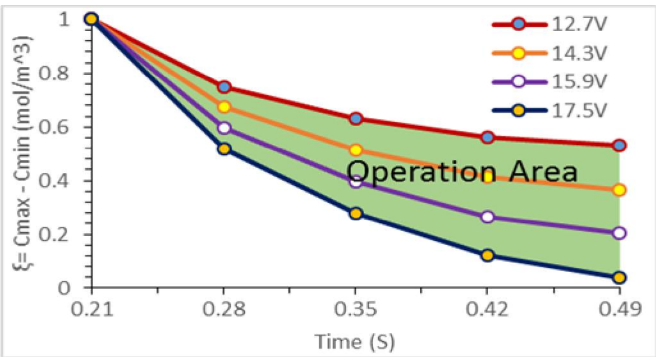

Figure 5. Mixing efficiency plot

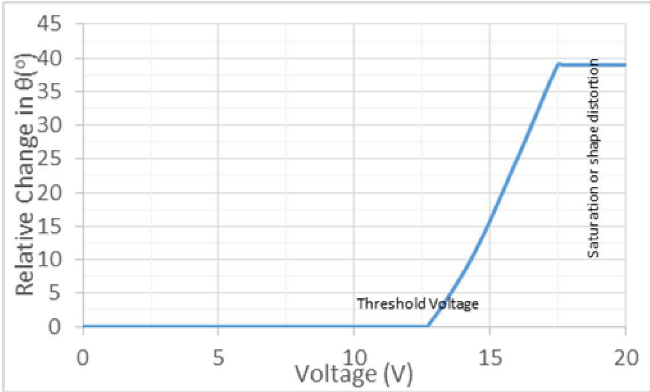

Figure 6. Contact angle modulation efficiency plot

Where ρ_1 and ρ_2 are the density of the fluid and air. u_1 and u_2 are the velocity of fluid and surrounding air respectively. n_1 and n_2 are the concentration of respective fluids. M_f is the mass flux, which we chosen zero, then the Eq 7 can be simplified as

$$u_1 = u_2$$
$$u_{mesh} = (u_1 \cdot n_1) \quad (8)$$

The fluid and dielectric interface defined as $\theta_c = \theta_w$, where θ_w is represented in Eq. 3

C. *COMSOL Physics for simulation*

AC/DC, Fluid Flow and Chemical Species Transport physics are used for simulation in COMSOL platform. In particular we use Electric Current (ec), Laminar Two-Phase Flow, Moving Mesh (tpfmm) for simulation of Lippmann-Young equation i.e change in contact angle for droplet deformation, additionally Level Set (tpf) with Electric Current (ec) for simulation of 2D droplet transport and Convection-Diffusion Equation (cdeq) for mixing two different concentrated droplets.

D. *Electrode Addressing*

It is a method to apply and switch the potential from current electrode to adjacent electrode. The efficient switching mechanism is required for mixing number of fluids. The efficient mixing can be possible by varying the space and time parameter. The Lippmann-Young Eq. can been simulated only by applying and removing potential from the same

Time (S)	Minimum Concentration (mol/m^3)	Maximum Concentration (mol/m^3)
0	0	1
0.07	0	1
0.14	0	1
0.21	0	1
0.28	0.27	0.79

0.35	0.36	0.64
0.42	0.44	0.56
0.49	0.48	0.52

Table 1: Concentration profile with respect to time at 17.5V.

Time (S)	Minimum Concentration (mol/m^3)	Maximum Concentration (mol/m^3)
0	0	1
0.07	0	1
0.14	0	1
0.21	0	1
0.28	0.15	0.9
0.35	0.20	0.83
0.42	0.23	0.79
0.49	0.24	0.77

Table 2: Concentration profile with respect to time at 12.7V.

Time (S)	12.7V	14.3V	15.9V	17.5V
0.21	1	1	1	1
0.28	0.75	0.67	0.59	0.52
0.35	0.63	0.51	0.39	0.28
0.42	0.56	0.41	0.26	0.12
0.49	0.53	0.36	0.2	0.04

Table 3: Differences of maximum and minimum concentration at voltages.

Voltage (V)	Contact angle (θ)	Relative Change in contact angle (θ)
0	130°	0°
12.7	126°	4°
14.3	114°	10°
15.9	90°	24°
17.5	51°	39

Table 3: Relative Change in Contact angle with respect to voltages.

electrode with respect to time parameter [32], whereas droplet transport and mixing has been simulated by switching the potential from current electrode to adjacent electrode with respect to space and time parameter (Figure 3). The time delay

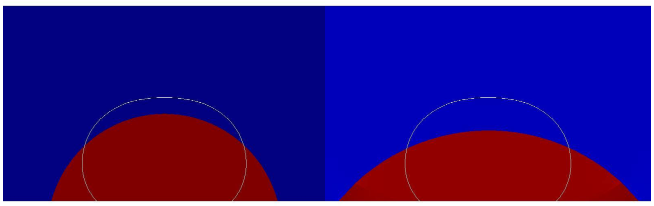

Figure 7. Shape of the droplet at 12.7V & 17.5 V respectively.

Figure 8. Shape of the droplet while voltage is under operational area (right) Distorted shape of the droplets under saturation zone (middle and left)

for switching and the electrodes activation time is very crucial parameter for application such as mixing and transport. By various testing and simulation we have obtained the effective delay of 0.07 s.

V. Result And Discussion

Droplet transport and mixing using the concept of Brochard's model and Lippmann-Young equation is successfully simulated on COMSOL Multiphysics platform. It has tremendous application in diverse fields. Figure 9(a), (b), (c), (d), (e), (f) and (g) demonstrates the transport and mixing of two discrete droplet having dissimilar concentration at different time scale. RGB color bar demos the concentrations of the fluids, whereas in top it records the maximum concentration and in bottom the minimum concentration. The resultant recorded maximum and minimum concentrations are presented in table 1 & 2 for 17.5V and 12.7V respectively. Its appearances deviation of ± 0.2 with expected average concentration i.e 0.5 mol/m^3.

The rainbow color bar is screening in Figure 9(i) for electric field, which we demonstrate only for one time scale i.e at initial switching electrode. And Figure 4 for velocity profile of the droplet. The efficiency plot with $C_{max} - C_{min}$ shown in Figure 5. Different simulation has been carried out with respect to voltages to find out the operational area under which the experimental must be conceded. The green shaded area on efficiency plot shows the operational area. It also present critical voltage for this simulation is 12.5 V, whereas in previous literature, 15V has been reported [31]. Experiment is not possible to perform above 17.5V science the shape of the droplet is distorting and missing the track which has been illustrated in Figure 8. Table-4 shows the change in contact angle and relative change in contact angle with respect to voltage respectively which is plotted in Figure 6. Critical and saturated shape of the droplet illustrated in Figure 7 where the white line present the unbiased shape of the droplet. Whereas the distorted shaper of the droplet are in Figure 8 while operating in saturation zone i.e. > 17.5V.

VI. Conclusion

In the present work, we have calculated the droplet change in contact angle with respect to voltage and time. Also we have simulated the time dependent transport of one droplets over a two-dimensional electrode array with respect to time and space. In addition, we have simulated the mixing of two droplets over two dimensional platform with respect to time and spacer by proper switching mechanism. Using the information gathered from the above simulation, the complex systems can be over simplified to address the challenges we mention in this paper.

The LoC does not involve with animal testing and human trial for pharmaceutical research which makes the process cost effective and time saving as well. The idea of home health care device can be extended for applications like RBC count for cancer patient.

The simulated result will also help for farther study, which enabling the integration of multiple subsystem modules into an automated next generation sequencing library sample preparation system. This emerging technology combines electronics with biology to open new application areas such as point-of-care diagnosis, on-chip DNA analysis, and automated drug discovery.

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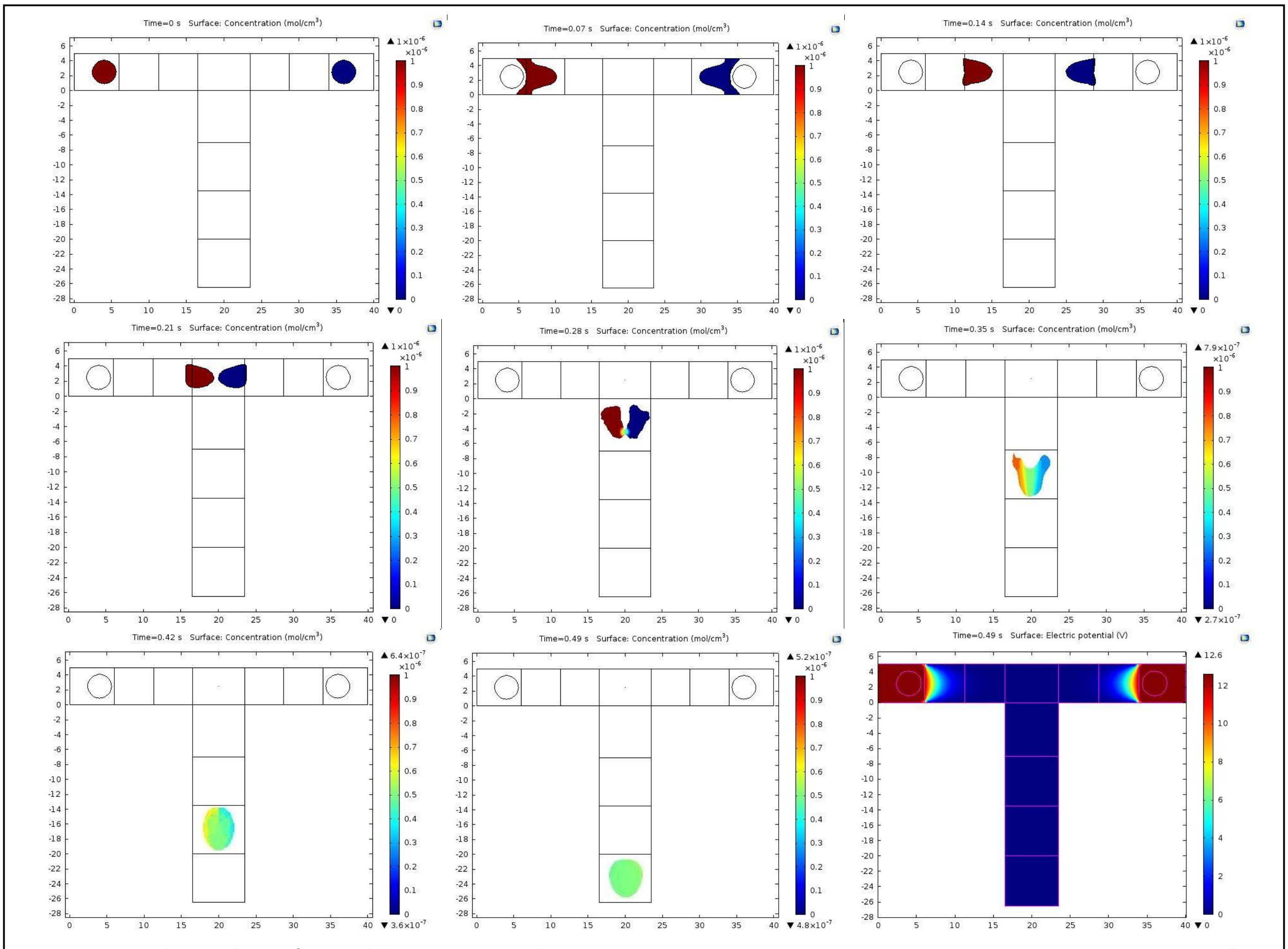

Figure 9. (a), (b), (c), (d), (e), (f), (g) and (h) are maximum and minimum concentrations i.e (1,0), (1,0), (1,0), (1,0), (1,0), (0.79,0.27), (0.64, 0.37) and (0.52,0.48) mol/m^3 at time 0.07, 0.14, 0.21, 0.28, 0.35, 0.42 and 0.49 Sec respectively. (i) The electric field simulation of 1st and 2nd electrodes.

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