The Effect of Latex Particles at the Edge of the Microelectrode in Lab on a Chip System

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Abstract—**The behavior of latex particles at the edges of microelectrode has been studied. The latex particles at the edge of microelectrode tend to possess greater variation in dielectrophoresis compare to the middle part of the microelectrode, which cause the particles to travel further distance. The particles effects near the edges at lower and higher frequencies were being observed and presented as an equivalent electric circuit.**

Keywords—Edge Effect; Electroosmotic Flow; Dielectrophoresis; Particle Image Velocimetry; Lab-on-a-chip.

I. INTRODUCTION

In the recent years, the explosion of interest in microsystem for chemical and biological analysis was the center of interest. This interest leads to discovery of "Lab-on-a-chip". Diverse functional units such as concentration, separation, and detection of particles can be integrated in the lab-on-a-chip. This technology leads to several applications in the field of engineering, medical, and chemical fields [1, 2].

Lab-on-a-chip worth awhile to miniaturize systems for fluid handling and processing; some of the technological developments headed toward a *terra incognita* where fluids behaved in a way of unknown from previous experienced with macroscopic system. By now, much of this *terra incognita* has been explored and solutions for many problems in microfluidics had been developed [3].

For moving and separating materials there are several ways, which includes electrophoresis (EP), AC Electroosmosis (ACEO), and dielectrophoresis (DEP). In this method, EP occurs due to the action of the electric field on the fixed, net charge of the particle, whilst DEP only occurs when there are induced charges, and only results in motion in a nonuniform field (this can be under a DC or an AC field). These forces used to move conducting electrolytes or particles along a network of narrow channels. Electric field-based manipulation and separation methods are highly suitable for integration into microchips [1, 4].

ACEO and DEP techniques of fluid motion cause a uniform velocity distribution across the microchannel, which is often advantageous. The electroosmotic velocity is given by

$$v_{eOf} = \frac{\epsilon \zeta E}{4\pi\eta} \qquad (1)$$

where ϵ is the dielectric constant of the fluid, η is the fluid viscosity, E is the applied field strength, and ζ is the zeta potential of the surface [5]. The electroosmotic mobility (μ_{e_0f}) is the electroosmotic velocity normalized by the applied field:

$$(\mu_{e_0f}) = v_{e_0f} / E \qquad (2)$$

In this study, latex beads were chosen to serve as the particles in the KCl medium of conductivity of 14.5 µS/m and their motion was compared with varying frequencies ranges in order to study the characteristic of electroosmotic flow. Latex was chosen due to its density, which has slightly greater than water (1050 kg m^{-3} compared to 1000 kg.m^{-3}) [6]. Its dielectrophoretic properties, which show polarization of particles is dominated by the surface conductance [7-9]. Dielectrophoresis arises via contact of the induced dipoles with non-uniform field. The output force is reliant on the gradient of the field squared ∇E^2 and the particle volume r^3, frequency and applied voltage [1, 9]. The dielectrophoresis force for spherical particle is written as

$$F_{DEP} = 2\pi\varepsilon_m r^3 \, Re[f_{CM}(w)]\nabla E^2 \qquad (3)$$

where r is the radius of the particle and ε_m is the dielectric constant in the medium, f_{CM} is the Clausius-Mossoti factor the effective polarizability of the particle. f_{CM} is depends on the applied frequency w. The term $Re[f_{CM}(w)]$ is bounded by -0.5 and 1. The sign of $Re[f_{CM}(w)]$ depends on the applied frequency. Dielectrophoresis is a local effect and the DEP force decreases rapidly away from the electrode [10]. As the particles moves under the influence of DEP, it can be assumed that the instantaneous velocity is proportional to the instantaneous DEP force (Yunus, 2014) so that for spherical particles such as latex

$$V_{DEP} = \frac{\pi a^3 \varepsilon_m Re[\bar{f}_{CM}]\nabla|E|^2}{6\pi\eta a} \qquad (4)$$

where V_{DEP} is dielectrophoresis velocity, a particle radius, f_{CM} Clausius-Mossotti factor, ε_m medium permeability. It can be seen that for a spherical particle the dielectrophoresis mobility depends on the radius of the particle squared and the real part of the Clausius-Mossotti factor, together with the permittivity and viscosity of the fluid [1].

The equations 1-4 are used to implement and target the parameters that may affect the particles in fluid. For instance, electrical field produces a force on the suspending medium causes variation in the charge density in the fluid. This electrical field produces force variations from the active microelectrode. The active and patterned microelectrode was designed to produce electrical field that can be controlled at different voltage and different frequencies. The examined microelectrode is with parameters of length and gap between the microelectrodes of 20 µm [1, 11, 12].

The analogy of electric circuit with microfluidic system will become handy and useful, as it will ease the understanding of microfluidic behavior under electrical field.

In this paper, the behavior of particles near the microelectrode will be presented, as well as the circuit analogy of electric circuit to microfluidic.

II. MATERIALS AND METHODS

A. Materials & Methodology

First of all, the microfluidic chip was fabricated on glass substrate using direct-write electron beam lithography with Ti/Pt layer (10/200nm thick) patterned. The microchannel was designed with a width of 500 µm and 40 µm height. The pattern of the microelectrode was as interdigitated microelectrode of 20 µm in width and the gap between the microelectrodes was 20 µm. The particles used in the electrolyte are latex particles with fixed particle size of 2 µm in diameter. The electrolyte used is Potassium Chloride (KCl) with conductivity of 14.5 µS/m, that acting as a medium (usually used in biology for normal cell respiration) and present viscosity. Zeta potential can be calculated based on surface charge density of particles as for low surface charge density the anomalous surface conductance becomes negligible [13, 14]. Part of the chip under microscope is shown below in Fig. 1, where the microelectrode, particles and microchannel are presented.

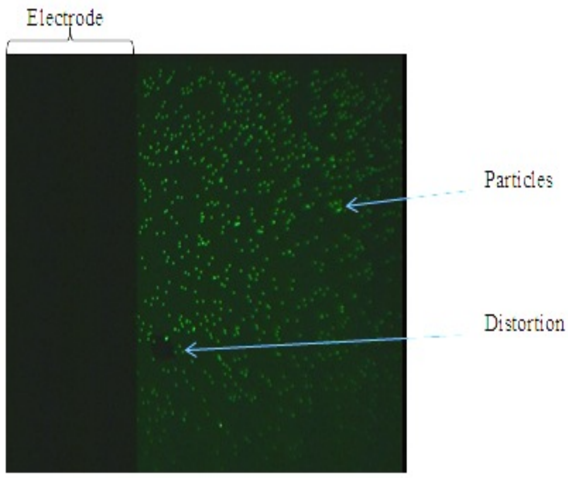

Fig. 1. Moving Latex Particles in KCl Solution

Fig. 1 shows the microelectrode on the left side, latex particles are the lighter dots, and note that the distortion is eliminated on the simulation to get better calculation of electrical field [4].

B. Characterizations

The microelectrode was supplied by an AC voltage of 2 Vpp throughout the test, with varying the frequencies between 10kHz until 500kHz. The acquiring videos are analyzed using Particle Image Velocimetry (PIV) software developed in MATLAB [15]; the assurance of consensus of the parameters used in the PIV software is critical to be able to get an acceptable comparison [16].

C. Setup

After chosen the materials to be used in this experiment, which includes, particles type from latex with size 2 µm, electrolyte KCl, microchannel width of 500 µm, microelectrode size of 20 µm, and voltage of 2Vpp. Then the videos for the selected time on the particles motion start to be observed and recorded.

After recording, the frequency value will be varied from 10kHz up to 500kHz. Then, the video will be extracted and analyzed using MATLAB v.2015b. Image pre-processing and post-processing are used to enhance the observation for PIV process in PIVLAB [16].

Finally, after getting all the data and represent them as chart; the behavior of particles can be observed and compared with the electric circuit. The analogy of the microfluidic to the electric circuit can be drawn as shown in section III.

III. RESULTS AND DISCUSSION

After defining all the parameters in the PIV software, the basic layout of one frame was picked randomly from 350 frames. For particles behavior near the microelectrode are shown on the left hand side of Fig. 2. The arrows show the direction of particles movement. The bigger the arrow means the more electrical field its possessed and cause the particles to move further/faster.

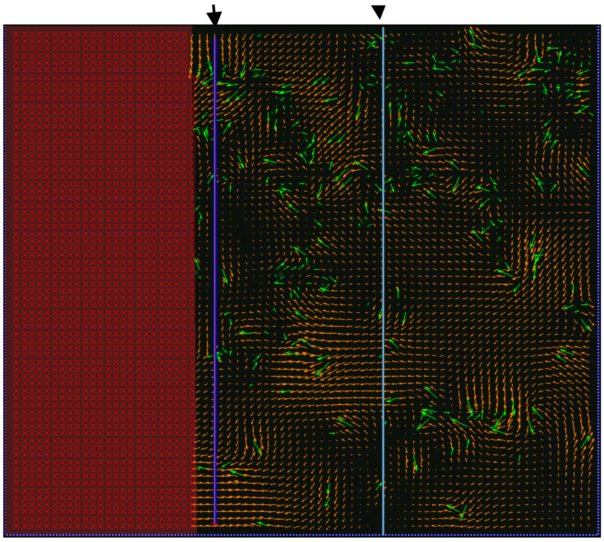

Fig. 2. Particles movement near and far from the electrode

Fig. 2 shows the microelectrode on the left hand side and it has been masked. The region of interest (ROI) is the electrolyte and the latex particles. Note that the particles movement near the edges of the microelectrode is slightly greater as compared to the middle part of the microelectrode.

The selected line near electrode was chosen to be 5 µm and the far selected line from electrode is chosen to be 35µm. Identifying the line near and far from the electrode will provide consistency along the simulation. This shows that the particles near the edges tend to get greater motion due to higher electrical field.

Moreover, by varying the frequency from 10kHz up to 500kHz the electrical field increases and the movement of latex particles increases as well. The increase rate is shown in Fig. 3.

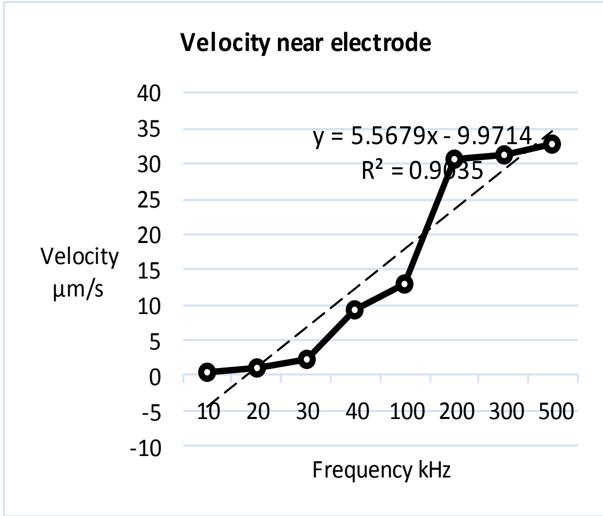

Fig. 3. Velocity vs Frequency Near Microelectrode

Fig. 3 above shows the velocity increases as the frequencies increases. The activity near the microelectrode is higher as compared with the one further away from the microelectrode. This was proven by [1, 12].

This is due to the fact that, as the particles are near the microelectrode, the DEP force is greater thus the electrical field is higher and causes the velocity of the particles increases i.e. the ACEO is present. The particles become hyper active as compared to the particles far away from the microelectrode as shown in Fig. 4.

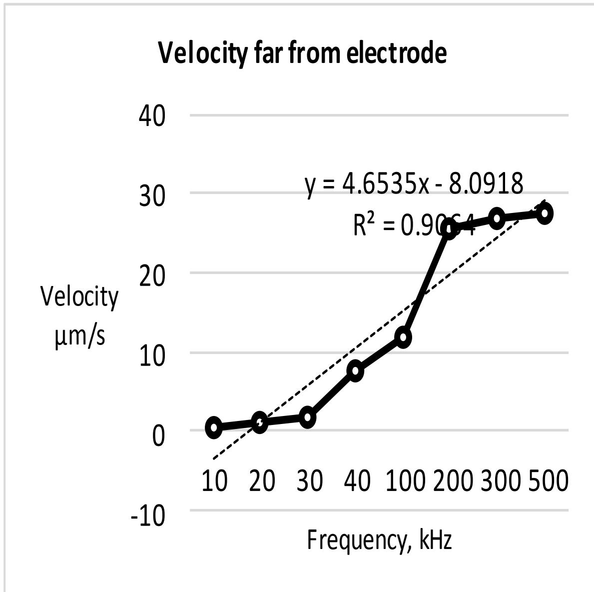

Fig. 4. Velocity vs Frequency Far from Microelectrode

Fig. 4 illustrates the velocity of particles under the effect of DEP and ACEO far from microelectrode is lower as compared to their velocity shown in Fig. 3. From Fig. 3 and 4, the velocity of particles near electrode will be 35 μm/s and far from electrode will be 30 μm/s at high frequency 500kHz.

The result shows that as the DEP and ACEO present with the frequency increases, the particles will move under certain velocity. Whenever the particles travel away from the electrode, although the frequency is increased, the particles velocity will decrease respectively due to weak DEP and ACEO further away from the microelectrode and this is proven by Clausius-Mossotti factor [17, 18].

Fig. 5 shows the velocity field as gradient representation to further study the response of particles near the electrode, particularly at the edges of the microelectrode.

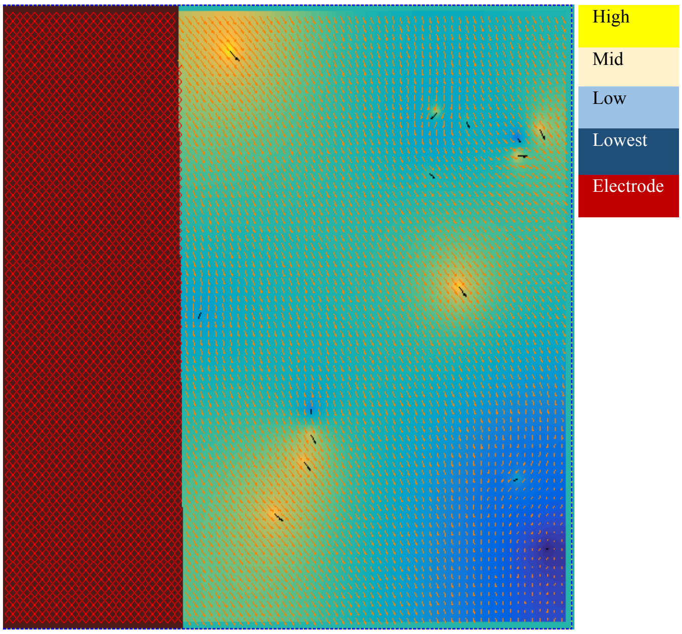

Fig. 5. Velocity field as color gradient μm/s

Fig. 5 shows the velocity field gradient is high at the edges of the microelectrode and if the gradient was taken from the top to bottom of the diagram, it decreases as it goes to the middle of the microelectrode. Then, it increases back as it goes near the edges of microelectrode.

To further verify the microelectrode edge effect, the data were collected for 350 frames. The results of the video when converted into series of images are used to study the particles effect on the edge of the microelectrode. Fig. 6 shows the data collected at minimum frequency 10kHz. In Fig. 6, the velocity versus distance was collected and examined at low frequency 10kHz near the microelectrode (at the selected line near the electrode as shown in Fig. 2).

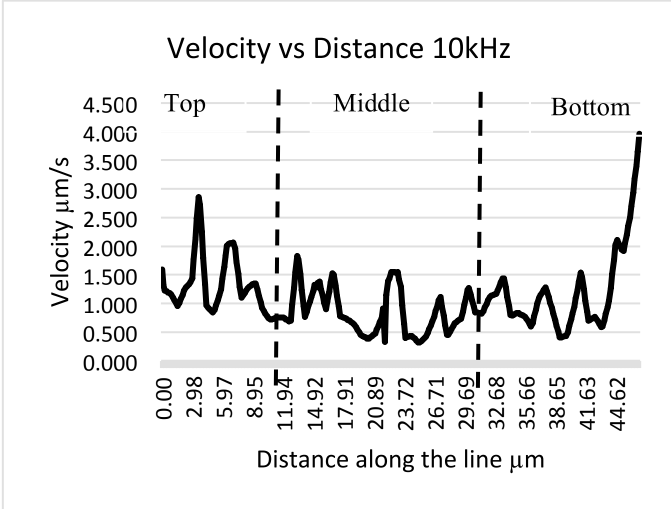

Fig. 6. Velocity vs Distance at 10kHz

The particles perform more motions near the microelectrode edges at the top and bottom sections of the Fig. 6.

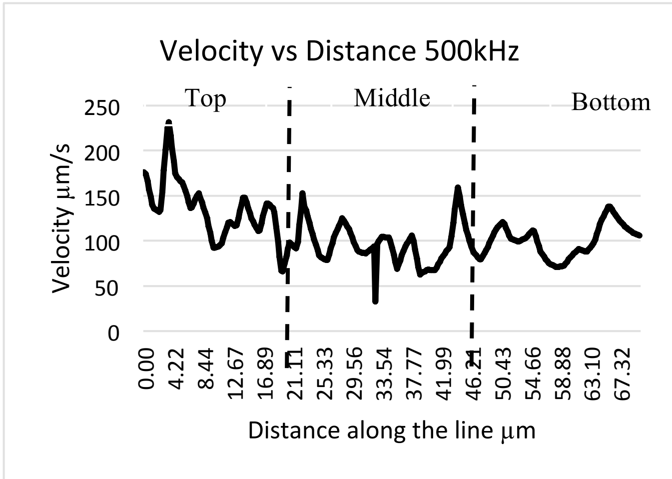

Fig. 7. Velocity vs Distance at 500kHz

Now when the frequency increase to 500kHz the electrical field will increase; thus, the velocity of latex particles will increase as shown in Fig. 7.

Fig. 7 shows the velocity vs distance at 500kHz, near the microelectrode (as shown in Fig. 2) at high frequency 500kHz. Note the velocity increases as the frequency increases. Also similar characteristic of velocity effect is observed at the edges of microelectrode. The velocity of particles is higher at the edges than at middle of the electrode. The top and bottom sections in Fig. 6 and 7 are representing the effect of the velocity near the edges of microelectrodes.

From all the results, an analogy circuit can be drawn as suggested by [1] between microelectrode to another electrode as shown in Fig. 8.

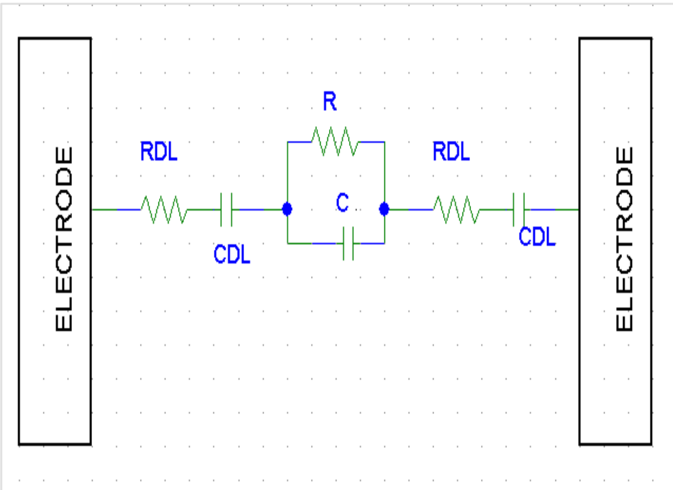

Fig. 8. Approximate circuit diagram for the system comprising an electrolyte between two metal electrodes [1]

Fig. 8 shows the dielectric measurements of medium suspensions of particles. It shows large capacitances at low frequencies, particularly at high suspending medium conductivities. This capacitance is due to the electrode polarization. Similarly, in dielectrophoresis measurements, as the frequency of the applied field is decreased the particles move more slowly since the potential in the suspending medium is reduced and the electric field is weaker. [1, 12, 19, 20].

When the charge accumulates at the interface between the electrode and the electrolyte, the system behaves like a capacitor with a non-uniform charge density. The potential across the charged layer declines exponentially from maximum at the electrode to almost zero at the middle electrode. Analogous to the charging of a capacitor; this is referred to as electrode polarization [20]. The consequence is that most of the applied potential is dropped across this capacitor so that the potential in the middle electrolyte may only be a fraction of that applied to the electrode (in the absence of electrode reactions).

Thus, in this paper, the possibilities envisioned by the characterization of lab-on-a-chip or microfluidic systems can cover a wide range of both scientific demands and industrial requirements, from life sciences, biomedical sensors, environmental engineering to fine chemistry, from food quality to other microbiology applications.

A firm and structured link between models and experimentation on lab-on-a-chip systems opens up the way for the study and characterization of lab-on-a-chip devices and phenomena from a point of view related to electrical and electronic theory. The electric analogy is one of the most extensively used methods for flow and particle motion effect modeling in microchannel based lab-on-a-chip systems. A lab-on-a-chip network is equivalent to an electric circuit, of which each component can be individually described by resistors, conductors and inductors. The analogy circuit near the edge of microelectrode can be represented by RC circuit as shown in Fig. 9.

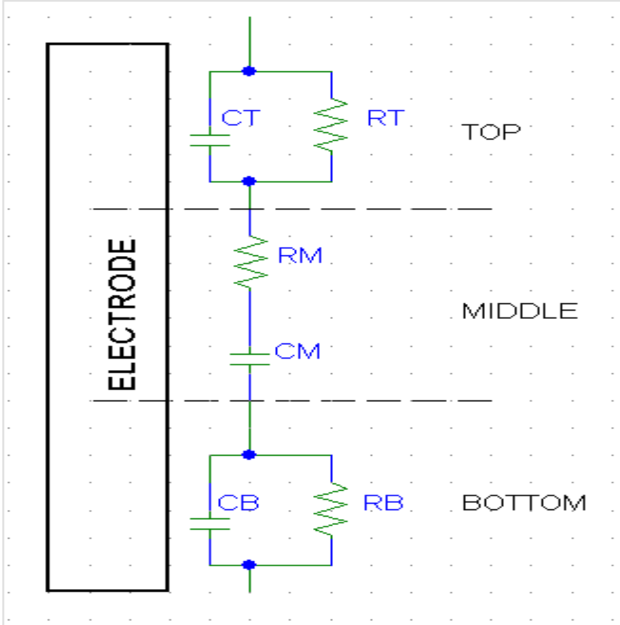

Fig. 9. Approximate circuit diagram for the system near microelectrode

The equivalent circuits are based on the behavior of latex particles near the electrode, these behaviors reflect on the electric component in two main cases:

A. At low frequency

At low frequency whereby f very small tend to zero, $f = 0$, the reactance value will be

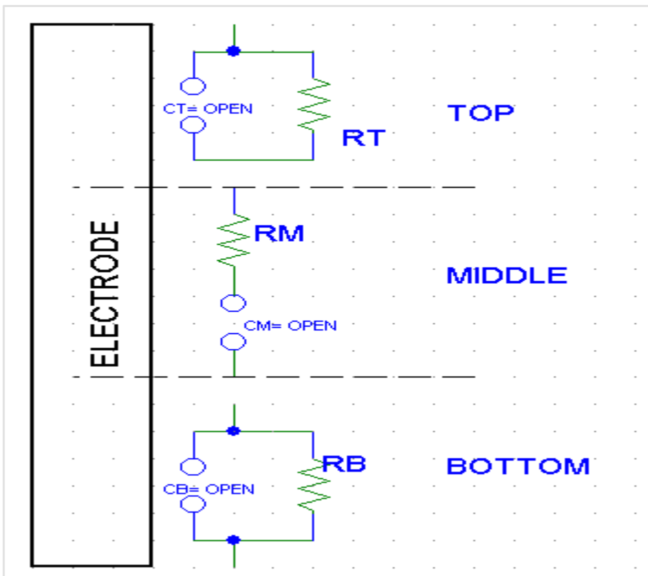

Fig. 10. Equivalent circuit at low frequency

$$X_C = \frac{1}{2\pi f C} = \frac{1}{2\pi(0)C} = \frac{1}{0} = \infty \qquad (5)$$

where is X_C reactance, f frequency, C capacitance. The equivalent circuit at $f = 0$, $X_C = \infty$ as shown on Fig. 10.

Fig. 10 explains that at low frequencies, the edges of electrode will behave as only real part resistance, *RT* at top of electrode and *RB* at bottom of electrode. There are the open circuit reactances. Similarly, the particles will move with small velocity values. On the other side, the middle portion of electrode will have very large impedance value as resistance *RM* and capacitance *CM* are presented. Likewise, the latex particles at middle section will have a very small velocity value, as the resistance is very high. The following equations will show the total impedance in parallel:

$$Z_T = R_T \backslash\backslash X_T \qquad (6)$$

where is Z is impedance, R resistance value, X_C reactance. So as the edge of electrode the equation in 6 will be

$$Z_T = R_T \qquad (7)$$

While the resistance will equal to R= RT or RB.

As for resistance at the middle electrode will be in series therefore:

$$Z_M = R_M + X_M \qquad (8)$$

Equation 8 shows that the resistance at the middle portion of electrode will be much higher compare to the edges of the electrodes. In the same way, the velocity of particles near the edge of electrode will be higher than the velocity in the middle section of the electrode.

B. At high frequency

At high frequency whereby f very large tend to ∞, $f = \infty$, the reactance value will be

$$X_C = \frac{1}{2\pi f C} = \frac{1}{2\pi(\infty)C} = \frac{1}{\infty} = 0 \qquad (9)$$

where is X_C reactance, f frequency, C capacitance. The equivalent circuit at $f = \infty$, $X_C = 0$ will be as shown in Fig. 11.

Referring to Fig. 11, at high frequencies the edges of electrode will act as there are no impedance, *RT and CT* at top of electrode and *RB and CB* at bottom of electrode, the reactance is short circuit. Similarly, the particles will move with greater velocity values.

Nevertheless, the middle portion of electrode will have an impedance value with resistance *RM* only. Equally, the latex particles at middle section will have a better velocity value compare to low frequencies, this is due to the resistance is small. The following equations will show the total impedance in parallel:

$$Z_T = R_T \backslash\backslash X_T \qquad (9)$$

where is Z is impedance, R resistance value, X_C reactance. So as the edge of electrode the equation in 6 will be

$$Z_T = 0 \qquad (10)$$

The resistance will equal to short circuit = RT or RB. As for resistance at the middle electrode will be in series thus:

$$Z_M = R_M + X_M \qquad (11)$$

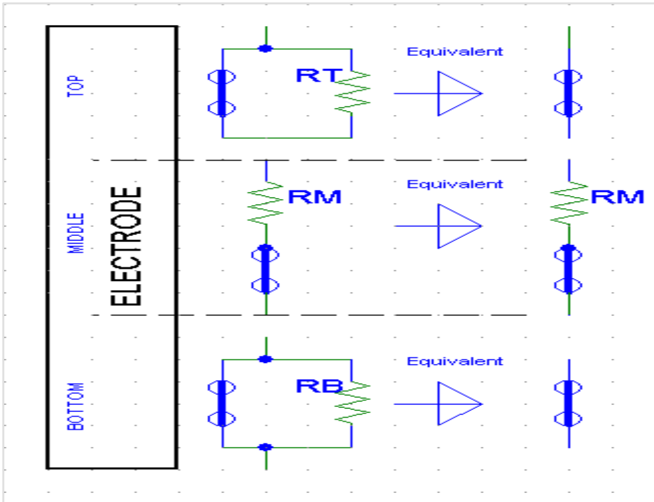

Fig. 11. Equivalent circuit at high frequency

$$Z_M = R_M + 0 \qquad (12)$$

Equation 12 shows that, the resistance at the middle portion of electrode will be much higher as compared to the edges of the electrodes. In the same way, the velocity of particles near the edge of electrode will be higher than the velocity in the middle section of the electrode.

IV. CONCLUSIONS

The effect of latex particles at the edges of the microelectrode was presented. It is shown that the latex particles at the edge of the microelectrode tend to possess greater variation in dielectrophoresis (i.e. related to the electric field strength and the velocity), which cause the particles to travel further distance.

This study shows that the microelectrode edges tend to exert greater electrical field as compared to the middle part of the microelectrode. This can give further studies, for instance, by using microelectrode with smaller cross sectional area or reducing the microelectrode into smaller electrodes to get greater edge effects, or apply external electrodes with greater edges to generate higher electrical field.

The importance of this study shows that the use of smaller microelectrode with less cross section area will provide better particles movement as the effect at the edge of the microelectrode is greater than the one in the middle of the microelectrode. It will also open future studies to concentrate on the microelectrode material and fabrication, particle size and type, particle concentration and reaction by varying voltage and frequency.

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