Proceedings of
The 5th National Congress on Fluids Engineering
March 26-28. 2008, Jeju, Korea

Research on the Electrical Charging of a Water Droplet on the Electrode and Droplet Actuation Method using Electrical Charge

Yongmi Jung[*], Hyunchang Oh[**] and Inseok Kang[***]

전극표면에서 액적의 충전현상과 이를 이용한 액적의 이동 방법에 관한 연구

정용미[*]·오현창[**]·강인석[***]

Key Words : *Electrical Charging(전기적 충전), Droplet Actuation(액적 이동), Microreactor(마이크로리액터), Coulombic force(콜롱힘), Droplet Manipulation(액적 조작), Dielectric Fluid(절연유체), Conducting Droplet(전도성 액적)*

Abstract

Droplet in miniaturized microfluidic systems have received much focused attention recently. In this work, electrical charging phenomenon of a conducting water droplet on the electrode under the dc electric field is studied and using this phenomenon droplet actuation method for microreactor applications is experimentally demonstrated. To find effects of key factors, the effects of electric field, medium viscosity, and droplet size are investigated. A scaling law of charging for the conducting droplet is derived from the experimental results. Unlike the case of a perfect conductor, the estimated amount of electrical charge (Q_{est}) of a water droplet is proportional to the 1.59 power of the droplet radius (R) and the 1.33 power of the electric field strength (E). (For a spherical perfect conductor, Q is proportional to R^2 and E.) It is thought that the differences are mainly due to incomplete charging of a water droplet resulted from the combined effect of electrochemical reaction at electrode and the relatively low conductivity of water. Using this phenomenon, we demonstrate the transport of the charged droplet and fusion of two oppositely-charged droplets. When electric field is subjected sequentially on the electrode, the charged droplet is transported on the electrode. For the visualization of fusion of charged droplets, the precipitation reaction is used. When subjected to a DC voltage, two droplets charged are moving and merging toward each other due to the Coulombic force and chemical reaction is simultaneously occurred by coalescence of droplets. It may be due to the interchange effect of charge. It is shown that the droplet can be used for microreactor where transporting, merging etc. of reagents constitute unit operation.

Introduction

When a fluid drop is suspended in an immiscible fluid under an externally applied electric field, the behavior of a charged droplet attracts much attention owing to its potential applications in various fields such as the bio-MEMS. [1~5] Recently, a droplet has also been considered as a candidate for a "micro-reactor" in microfabricated devices. Electrical manipulation of a charged droplet may be used in the design of such systems. However, the issue of the charging process of a fluid particle has hardly been considered. Regarding the problem of charging of a particle at electrode, studies have mostly been limited to the solid particle cases. [6] Recently, the issue related to the behaviors of a conducting droplet under electric field has been studied extensively both experimentally and theoretically.[7,8]

In this work, therefore, we experimentally studied the electrical charging phenomenon of a micro-sized conducting droplet on the electrode and using this phenomenon, we demonstrated droplet actuation method for microreactor applications.

Material, Method and Experimental Setup

1. Experimental setup and conditions

In the experiment, we measure the velocity of a droplet moving between the electrodes. The velocity is converted to the amount of a charge as will be shown later.

The schematic diagram of the experimental setup is shown in Fig. 1. To observe translation and behavior of a droplet, a high speed CCD camera (Photron Fastcam 1024 PCI Model 100K) at 5000fps is mounted on the microscope. The velocity is extracted using the image analysis techniques. Single DI (de-ionized) water droplet and silicon oil (KF-96 series produced from Shin-Etsu Silicone) are used as the conducting droplet and the dielectric fluid medium respectively. To observe the effects of various parameters, the viscosity of medium, the size of droplet, and the applied

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[*] 포항공과대학교 화학공학과, pshyche@postech..ac.kr
[**] 포항공과대학교 화학공학과, arthur@postech..ac.kr
[***] 포항공과대학교 화학공학과, iskang@postech..ac.kr

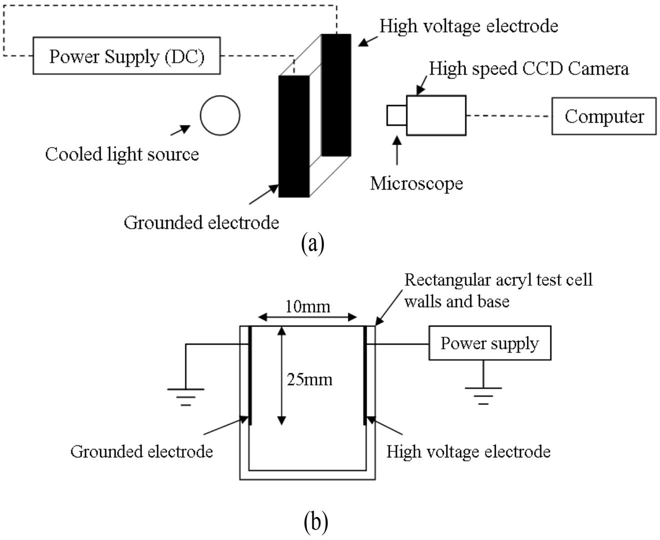


Fig 1. The schematic view of the experimental setup. The cell sketch is not to scale. ((a): the schematic view of the experimental apparatus, (b): Details of the microscopic test cell)

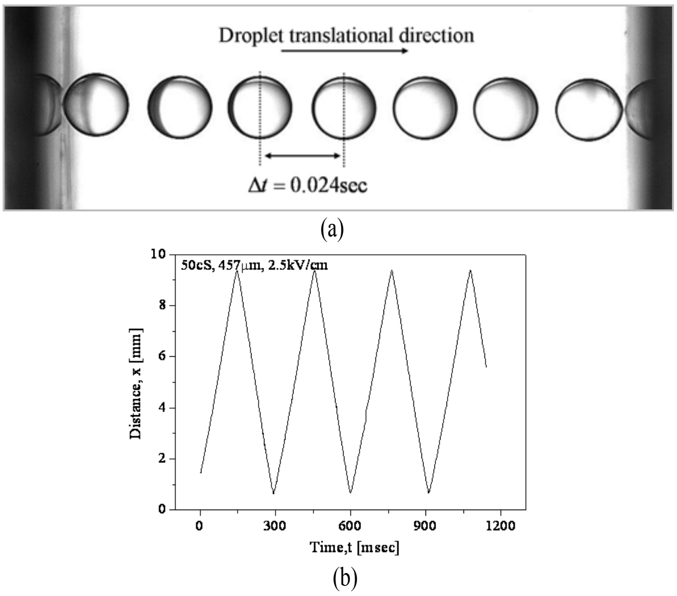


Fig 2. The sequence of photographs of a droplet moving from the left (+) to the right (-) (a) and the position of droplet from the positive electrode as a function of time.(b)

voltage are changed systematically. We use three kinds of silicon oils (ϵ =2.75ϵ_0, where ϵ_0=8.854×10^{-12} F/m) with viscosities of 50, 260, and 1000cS. The volumes of the Deionized water droplets (ϵ =77.75ϵ_0) are varied with 0.2, 0.4, 0.8, and 1.6μl. The corresponding drop radii are 363, 457, 576, and 726μm, respectively. Also, we apply the external voltages of 2, 2.5, 3, and 4kV across the fixed distance between two electrodes of 10mm.

The fusion of two oppositely-charged droplets using electrical charge. is demonstrated For the visualization of fusion, the precipitation reaction is used. Two droplets containing sample and reagent individually are positioned in front of each electrode for the charging individually. When subjected to a DC voltage, two oppositely-charged droplets are moving toward each other due to the coulombic force and chemical reaction is occurred by coalescence of droplets. High speed CCD camera is used at 6000 fps for the precise observation.

2. Estimation of amount of charge on the droplet

An initially uncharged conducting water droplet suspended in silicon oil starts to move slowly when a DC electric field is applied. At the moment a droplet touches the electrode surface, electrical charging occurs between the electrode and the droplet. Then the droplet, which has the charges of the same sign as the electrode, is repulsed and moves toward the opposite electrode. A droplet, which arrives at the opposite electrode, discharges its own charges and acquires new charges from the electrode. Then the droplet is also repulsed and translated. This process repeats itself. This is the so-called contact charging process.

When the droplet size is small enough, the shape is spherical and the inertial effect may be neglected. In the middle region of the two electrodes, it can be assumed that the electric field is uniform and the droplet moves with a constant velocity. We consider now the force balance for the droplet,

$$\sum F = F_D + F_Q = 0 \tag{1}$$

$$F_Q = QE_\infty \tag{2}$$

In the above, the drag force is assumed to be given by the Hardamard-Rybczynski solution[9],

$$F_D = 4\pi\mu a Uc \quad \text{where } c = \frac{3\lambda+2}{2(\lambda+1)},\ \lambda = \frac{\mu_w}{\mu} \tag{3}$$

From the force balance, we have the following formula for estimation of the amount of charge in terms of droplet velocity,

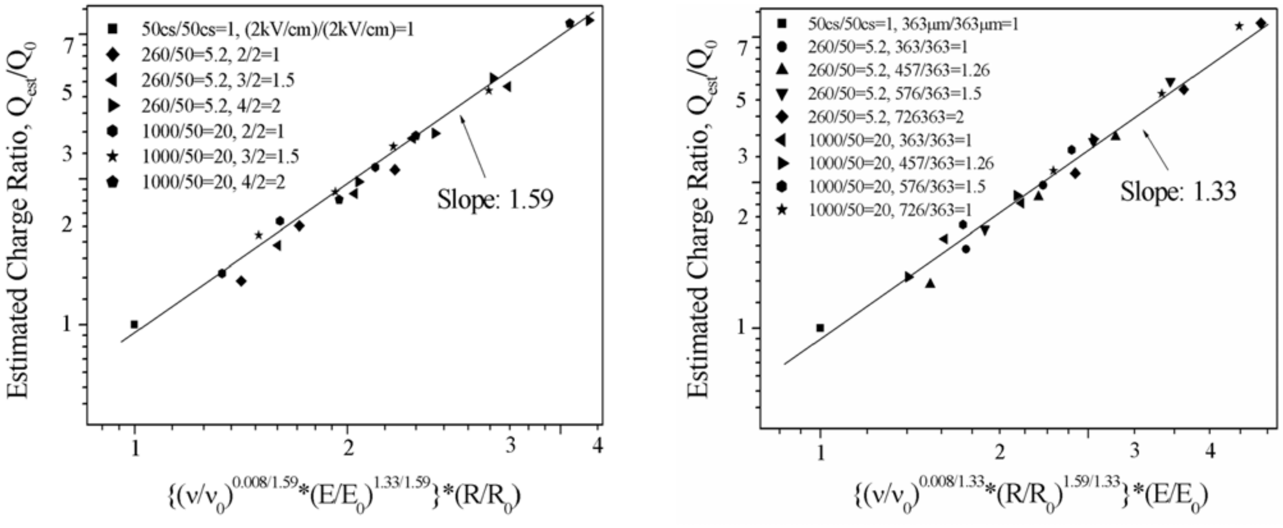
$$Q_{est} = \frac{4\pi\mu a Uc}{E_\infty} \tag{4}$$

In the above, Q_{est} is the estimated electrical charge on the droplet, E_∞ the magnitude of the applied external field, μ_w the viscosity of water inside the droplet, μ the viscosity of the medium, a the droplet radius, U the droplet velocity.

Results and Discussion

1. Translational motion of a droplet between electrodes

Figure 2(a) is the sequence of pictures of a half-cycle of the time-periodic motion. The droplet near the electrode becomes elongated and makes a tip facing the electrode. This is because a droplet is deformable and the electric field is very asymmetric near



(a) (b)

Fig 3. The dependence of the estimated charge (Q_{est}/Q_0) on the droplet radius (R/R_0) (a) and the electric field (E/E_0) (b). The subscript "0" stands for the reference state of E_0=3kV/cm, R_0=362μm, and medium viscosity 50cS with the estimated charge Q_0 =1.03*10^{-11}C.

the electrode. The drop tip becomes sharper and sharper and eventually touches the electrode. At that time, the oppositely-signed charges on the droplet are discharged at the electrode and the same-signed charges move to the droplet. This is the process of electrical charging.

Figure 2(b) shows the droplet position as a function of time for a typical case. The droplet shows a very regular periodic motion between the electrodes and reaches a constant velocity near the center. The constant velocity is used for estimation of the amount of charge on the droplet by using Eq. (4).

2. The estimation for the amount of electrical charging acquired at an electrode and the scaling law

To estimate the amount of charge, the moving velocity of a droplet in the middle region of the electrode cell is measured. The measured velocity is used to estimate the charge amount by using the force balance by Eq. (4) The experimental results for the amount of electrical charging have been summarized in the form of a scaling law.

In Fig. 3(a), the dependency of charging amount on the droplet radius is shown. In order to show the dependency in a more convincing way, the x-axis (abscissa) variable is modified by multiplying the factors in terms of other parameters (the kinematic viscosity ratio and the electric field ratio). In a similar way, the effect of electric field is shown in Fig. 3(b). From Figs. 3(a) and 3(b), we can see that the amount of electrical charging increases with the size of the droplet and the applied electric field strength. On the other hand, the viscosity of the dielectric fluid medium is not a key factor in the electrical charging process for the parameters in the present study.

Summarizing the experimental results, a scaling law for the amount of the electrical charging has been derived as (see Fig. 4)

$$\frac{Q}{Q_0} = C\left(\frac{R}{R_0}\right)^{1.59}\left(\frac{E}{E_0}\right)^{1.33} \quad (5)$$

where the subscript 0 stands for the reference state (R_0=363μm, ν_0=50cS, E_0=2kV/cm, Q_0=1.03*10^{-11}C) and C is a constant that depends on the viscosity ratio to the reference medium viscosity. The value of C changes slightly as, for μ/μ_o=1, C=1, for μ/μ_o=5.2, C=1.0147, and for μ/μ_o=20, C=1.045. Since the viscosity effect is very weak, the viscosity effect is treated in the way shown above.

According to Cho [6], the amount of the induction charging of a spherical perfect conductor is proportional to the square of radius and the electric field. The scaling law for the present water droplet is a bit different from the perfect conductor case in the exponents. In the water droplet case, the exponent for the effect of the droplet radius is decreased (2.0 -> 1.59), while the exponent for the effect of the electric field is increased (1.0 -> 1.33). It is thought that the differences may be mainly due to incomplete charging of a water droplet resulted from the combined effect of electrochemical reaction at electrode and the relatively low conductivity of water.

3. The fusion of two oppositely-charged droplets

When subjected to a DC voltage, two droplets charged are moving and merging toward each other due to the Coulombic force.

For merging two droplets, these droplets are charged individually with opposite-signed. Two opposite-charged droplets are moving toward each other by the Coulombic force and chemical reaction is occurred simultaneously by coalescence of droplets. (Fig.5) It may be due to the interchange effect of charge.

Compared with EWOD, one of advantages of this method is no contamination of substrate. Because the droplet is deformed the cusped shape by electrical charge, a droplet hardly adheres on the electrode.

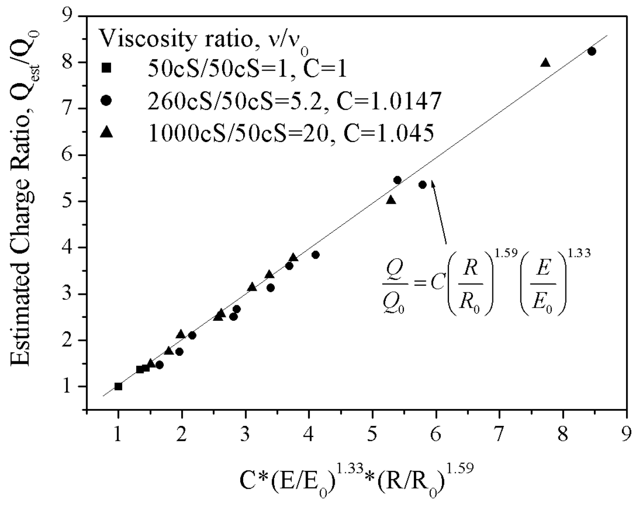


Fig 4. The graph of the scaling law summarizing the experimental results.

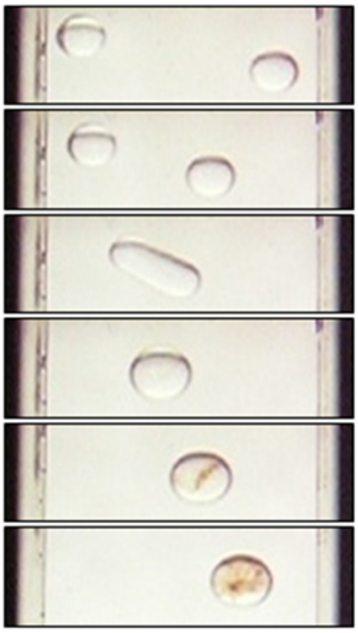


Fig 5. The sequence of photographs of fusion of two oppositely-charged droplets

Concluding Remarks

In this study, electrical charging of a water droplet at the electrode has been studied experimentally and translation and fusion of charged droplets are demonstrated.

The experimental results show that the electric field strength and the droplet size are the important key factors to the electrical charging process. On the other hand, the viscosity of the medium fluid does not have a significant effect in the parameter range of the present study. The experimental results are summarized in the form of a scaling law. In the scaling law, the amount of electrical charging of a water droplet is proportional to the power 1.59 of the droplet radius and the power 1.33 of the electric field strength. In the case of a perfect conductor sphere, the charge is proportional to the square of radius (the power 2) and proportional to the electric field (the power 1). It is thought that the fundamental differences are due to other reasons such as the ionization reaction at the electrode and the relatively low electrical conductivity of the water droplet.

Also, we demonstrate the proofs-of-concept for handling a conducting droplet using electrical charge. By the Coulombic force, two oppositely- charged droplets is successively merged in our experiment. Further studies of deeper level are definitely needed for thorough understanding.

It is thought that the electrical charging phenomenon can be used as a tool of transporting a single micro- or nano-liter droplet in a micro-channel without moving the medium fluid. Especially, when a conducting droplet is used as a tool of transporting bio-particles like DNA molecules, they are safe inside the droplet against the strong external electric field. Inside the conducting droplet, there is virtually no electric field. This fact may also find many applications.

Acknowledgements

This work was supported by the grant R01-2004-000-10838-0 from KOSEF. This work was also supported by the grant from Center for Ultramicrochemical Process Systems (CUPS) sponsored by KOSEF and the grant by BK21 program of Ministry of Education of Korea. The authors greatly acknowledge the financial supports.

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