

# Investigations on the Evaporation of Charged Droplets on Hydrophobic Surface

**Yajun Fan, Junfeng Wang\*, Yuanping Huo, Ziwen Zuo**

School of Energy and Power Engineering, Jiangsu University  
301 Xuefu Road, Zhenjiang, China

fanyajunjerry@gmail.com; wangjunfeng@ujs.edu.cn\*; huoyuanping@gmail.com; ivenzuo@gmail.com

**Abstract** - The evaporation process of charged droplets with different conductivity is experimentally studied in details. By means of high-speed microscopy camera, the evaporation characteristics including contact angle and height of a charged droplet under different applied voltages have been visualized and measured. According to the characteristics, the charged evaporating process is concluded by us as two stages: the stationary stage and the accelerated stage. The study reveals that electric field significantly influenced the evaporation of droplets and need to be considered when quantifying the evaporation process. The evaporating time of water droplet is almost double the time of hydrochloric acid (HCl) droplet at the same voltage. The evaporating rate increases dramatically with the increase of the voltage. The ion concentration of charged droplets is also shown to have a significant effect on internal circulations. The results indicate that electrical force promotes the movements of ions which determine the evaporation rate of charged droplets. It is assumed that micro electro-hydro Dynamics (EHD) such as the droplet internal flows have large impact on the evaporation process of charged droplets.

**Keywords:** Charged droplets, Evaporation, High-speed microscopy, Electro-hydro Dynamics (EHD).

## 1. Introduction

The evaporation of a sessile droplet on different hydrophobic surfaces has been experimentally investigated (Ghasemi H et al., 2010; Dugas V et al., 2005). The natural evaporation of a droplet on various surfaces is a fundamental problem and has been studied intensively for a wide range of technological and biological applications; e.g., inkjet printing, spray painting, DNA stretching (Dugas V et al., 2005) and cell patterning (Craster R.V et al., 2009). Droplet evaporation is a common and complex diffusion phenomenon that is controlled by the physical properties of the liquid itself, such as the molecular weight, density, diffusion coefficient in air, and heat of vaporization (Ying-Song Yu et al., 2012).

As early as 1977, Picknett and Bexon (1977) reported that in the evaporation of drops on surfaces three different evaporation modes were distinguished: constant contact area stage (CCR, or pinned contact line stage), constant contact angle stage (CCA, or depinning stage) and mixed stage. In 1993, Birdi and Vu deduced that evaporation process of liquid droplet on smooth solid surfaces has two different situations depending on the value of contact angle (Birdi et al., 1993). When contact angle  $< 90^\circ$  CCR mode is available; while CCA mode is for contact angle  $> 90^\circ$ . Shanahan and Bourgès (1994) found that the evaporation process of droplets were rather complex than remained one simple mode. It would change based on the time constant. Through studying the evaporation process on rough and smooth surfaces, they concluded changed law of contact angle, contact area radius and droplet height with evaporation time. They found the pinning stage (CCA) occupied the longest time of the droplet evaporation lifetime.

In general, the surface is generally divided into two groups: the hydrophilic surface which is the surface with a water contact angle below  $90^\circ$ , and the hydrophobic surface when the contact angle is above  $90^\circ$ . Recently, studies on hydrophobic surfaces have been extensively performed. A hydrophobic surface is notable as it has the features of water repellency and low surface energy. Additionally, studies have conducted about the droplet evaporation on the hydrophobic surfaces with structures (Shin D H et al., 2010). However, the external electric field was not applied in Shin's experiments and the impact of electric force was ignored.

Certainly, the droplets under electrostatic forces have also been investigated in recent literatures by Chen et al (2013). That study forced on the early spreading of a liquid drop on a solid surface affected by an electric potential.

For industrial heat transfer applications, evaporations of charged droplets are of fundamental interest, since commonly used surfaces are (naturally) charged (Chen L et al., 2013 ). Along with the development of charged technology for sessile droplets, it is very significant in theory and valuable in practical area to research delicately the evaporation process of sessile charged droplet.

It is known that the evaporation characteristics of a charged droplet are much more different from the natural evaporation process. As the behaviors of charged droplet would be noticeably complex during the evaporation process, further investigations for charged droplet evaporation should be conducted.

In this report, the evaporation process of charged droplets with different conductivity is experimentally studied in details. It mainly forces on the based performances such as changes of evaporating rate, droplet height and contact angle. And the impacts of voltage and concentration on evaporating velocity are shown in this studies.

## 2. Experiments

In this experiment, we measured the contact radius, droplet heights and contact angles of a charged droplet during the evaporating process (Fig. 2). The diagram of the experiment setup is shown in Fig. 1.

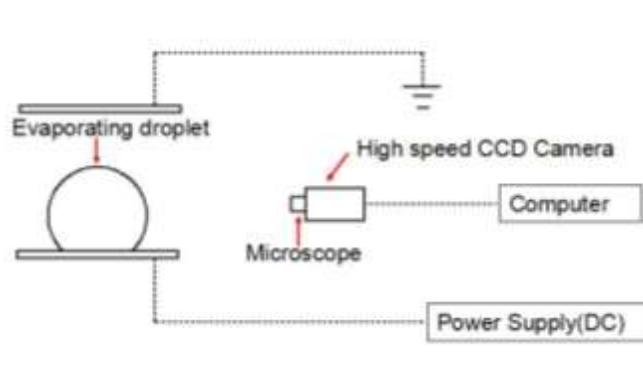


Fig.1. The schematic view of the experimental setup.

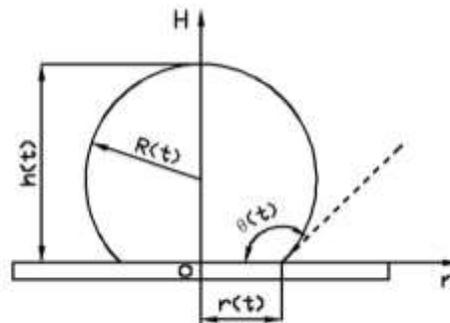


Fig.2. Side view of spherical droplet.

The sessile droplet (water/HCl) that was placed on the same hydrophobic surface was created by a syringe pump. All droplets were almost of equal weight and the initial contact angle was almost  $>90^\circ$  that could meet requirements of the experiments. Also, the surface was not heated. In the experiments, the droplets and surface were under the required humidity and controlled room temperature. The temperature and relative humidity of the environment were maintained at  $24^\circ\text{C}$  and 20% respectively. Then the surface was connected to a DC voltage power supply to apply an external electric field. By means of a high-speed

microscopy camera, the evaporation behavior of a charged droplet has been captured and visualized. After obtaining evaporation images, contact angle, contact area radius and droplet height could be measured by computers.

### 3. Results and Discussion

The images of droplet evaporation captured in our experiments under different electric field are shown below (Fig. 3 and Fig. 4). It is evident that the evaporation behaviors of the charged droplet are vastly different from those of the natural droplet. The HCl droplet completely evaporates at 3180s (Fig. 4.(a)), which is the longest period of evaporation time among the tests in the study. While the evaporation time of charged HCl droplet decreases dramatically at 900s under 4kV (Fig. 4.(b)), which is just 1/3 of evaporation time of natural HCl droplet. It is the same as the process of water droplet which is just 480s under 10kV (Fig. 3.(c)). The evaporation time of natural droplet (Fig. 3.(a)) is three times than charged droplet (Fig. 3.(c)). It is evident that electric field significantly influences the evaporation of droplets and need to be considered when quantifying the evaporation process. It is assumed that the electric force would make greater contributions to droplet evaporation than others at the controlled room temperature and the required humidity.

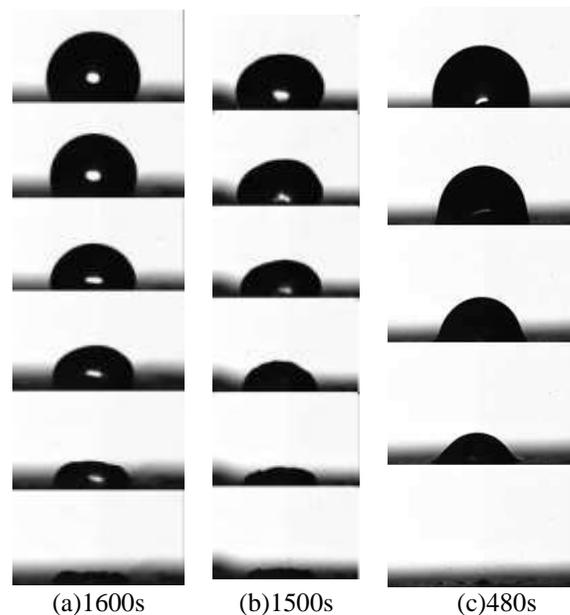


Fig.3. Images of water droplet evaporated under different electric field (a) 0kV, (b) 4kV, (c) 10kV.

Considering the Fig.3 and Fig.4, it is obvious that the evaporation rate of charged HCl droplet is noticeably sharper from 3000s to 900s that is more effective than the charged water droplet at the same experimental condition. Fig. 3.(b) shows the evaporation process of charged water droplet under 4kV that completely evaporates at almost 1500s. While charged HCl droplet just evaporates 900s at the same voltage (Fig. 4.(b)). It is evident that HCl droplet is more active under the same electric field than water droplet. It is assumed that the ions concentration play a big role in the sessile droplet evaporation in this study.

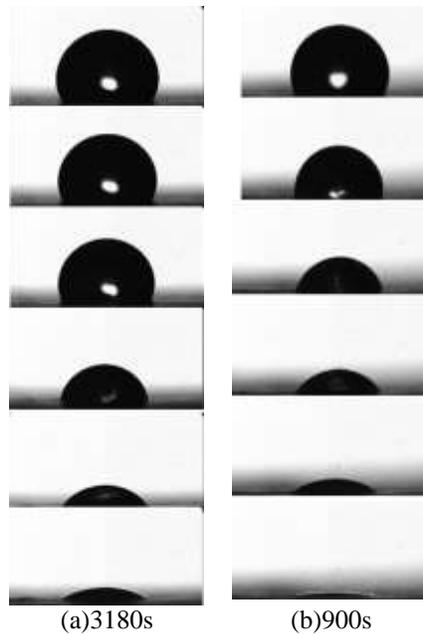


Fig.4. Images of HCl droplet evaporated under different electric field (a) 0kV, (b) 4kV.

According to previous studies, natural evaporating droplets generally have two stages, which are characterized by pinning and depinning of the contact area radius (Picknett et al., 1977 ). At present, most available models focus on the initial pinning stage as it is assumed to occupy 90%-95% of the droplet lifetime (Hu et al., 2002 ). It can also be observed in the charged evaporation processes.

Fig.3 and Fig.4 are the line graphs of water and HCl droplet changes in droplet height and contact angle during the evaporation process respectively. In the natural evaporation process, the pinning stage last much longer time than the depinning stage, about 80%-90% of the droplet lifetime, which makes good agreement on previous research results. In order to describe the process better, it is concluded by us as two evaporation stages: the stationary stage and the accelerated stage, no matter whether it is under electric field. The contact angle of the natural droplet gradually reduces due to evaporation with a decreasing droplet height. The contact angle and droplet height slowly and steadily decrease in the first stage, then, the angle and height drastically shrink.

However, when the charged droplet (water/HCl) was experimented, the evaporation duration of the stationary stage would be reduction under the electric field. As the voltage increases, the lasting time of two stages tends to be equal under the electric field. The differences between the two stages tend to be less.

In the Fig.5 and Fig.6, we can discern significantly different tendencies among the droplets under different electric field. The angle and height of the droplet decline slowly in the first stage when the electric is not applied. Although the evaporation rate in the accelerated stage is very fast, the overall trend greatly reduce the evaporation efficiency. When the droplet is under a high voltage, the second stage plays a more and more important role in evaporation process. Even it seems to skip the first stage and directly be into the second stage and then the droplet evaporates quickly(water,10kV; HCl,4kV).

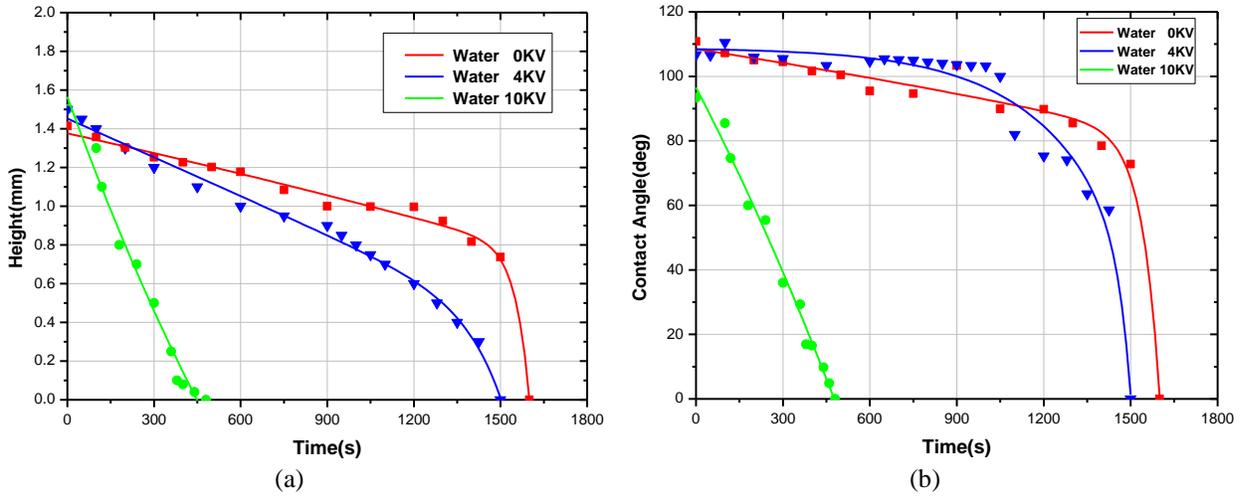


Fig.5. Changes of water droplets in (a) height and (b) contact angle.

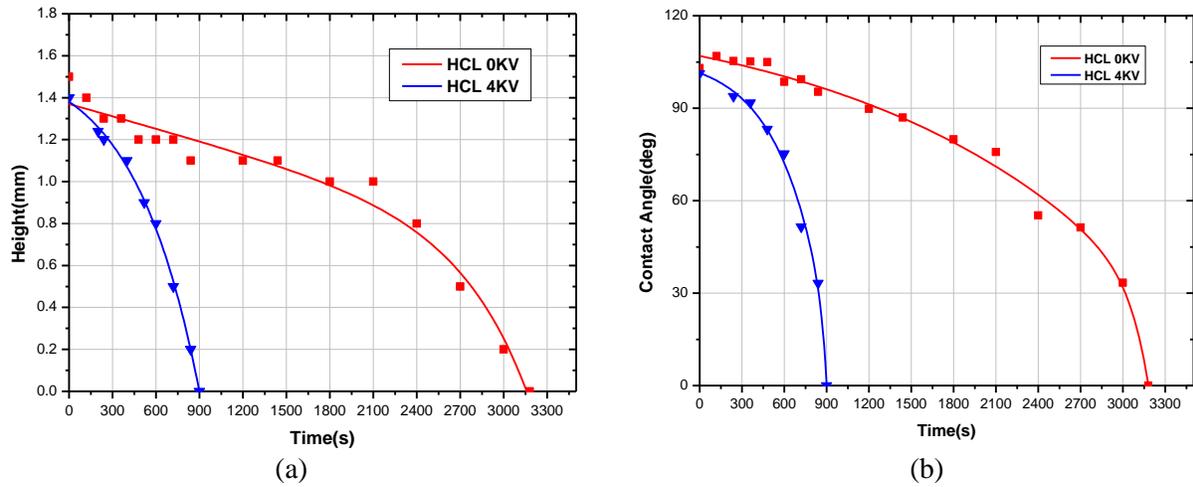


Fig.6. Changes of HCl droplets in (a) height and (b) contact angle.

It is interesting that HCl droplet started to vibrate and evaporated very quickly when we applied a higher voltage. And the higher voltage was applied, the evaporation speed was quicker. Certainly, the outside vibration of the droplet speeds up the evaporation rate by heat and mass transfer. But it is assumed that micro electro-hydro Dynamics (EHD) such as the droplet internal flows have large impact on the evaporation process of charged droplets. Past studies shows that internal circulation would be observed in a single droplet evaporating process. Deepak et al (2012) found that liquids would exhibit intense internal circulation during evaporation. In our experiments, it is assumed that the electrical field has a positive impact on the droplet internal flow. With the increase of voltage, electrical force promotes the movements of ions and encourages the formation of circulations inside the droplet. The electric force speeds up the velocity of internal circulation then improves the evaporation efficiency. It makes the second stage start earlier that is much different from traditional droplet evaporating process.

It indicates that the movements of ions forced by electric field inside the droplet accelerate the evaporation speed of droplets considerably. In order to gain further progress, we are making efforts to capture the internal flow and streamlines of charged droplet evaporation process by the technology of PIV in the future researches.

In order to directly reflect and compare the evaporation velocities, the initial contact angle and droplet height were converted into the initial droplet volume by the equation (1) as

$$V = \frac{\pi}{6} h(3r^2 + h^2) = \frac{\pi r^3}{3} \frac{f(\theta)}{\sin^3 \theta} = \frac{\pi h^3}{3} \frac{f(\theta)}{(1 - \cos \theta)^3} \quad (1)$$

Where  $f(\theta) = 2 - \cos \theta(3 - \cos^2 \theta) = (2 + \cos \theta)(1 - \cos \theta)^2$

By solving the equation, Eq. (1), we can get the droplet volume with the angle and height, theoretical solution of velocity can be given as

$$v = \frac{V}{t} \quad (2)$$

As an intuitive evaporating parameter, The  $v$  would speed up as the applied voltage increases.

The diagram is shown about the relationships of evaporation rate and voltage and concentration (Fig.7).

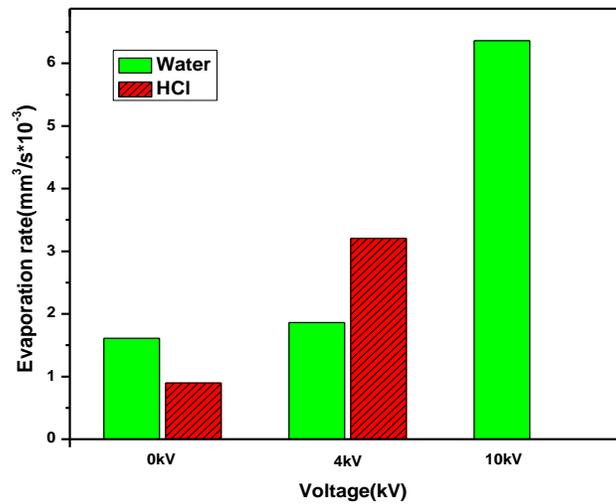


Fig.7. The relationships of evaporation rate and voltage and concentration.

It is intuitive that the voltage and concentration speed up the evaporating rate. As shown above, the evaporating velocity can be accelerated whether it is water or HCl. And the velocity of HCl droplet under 4kV is quicker than that of water droplet. Furthermore, the slope of velocity of HCl droplet is steeper during the same evaporation process indicating that the concentration can increase the evaporation rate.

#### 4. Conclusion

Experiments of charged droplet evaporating on the hydrophobic surface have been conducted. The characteristics of charged droplet evaporation on a hydrophobic surface are more complicated. The evaporation time of charged droplet is much less than natural droplet. It is evident that electric field significantly influences the evaporating efficiency of droplets and need to be considered when quantifying the evaporation process.

It is shown that the evaporation rate of charged HCl droplet is noticeably sharper than the charged water droplet at the same experimental condition. It is evident that HCl droplet is more active under the same electric field than water droplet. We assumed that the ions concentration play a big role in the sessile droplet evaporation in this study.

The evaporating process can be divided into the two stages: the stationary stage and the accelerated stage. The evaporation duration of the stationary stage would be reduced under the electric field. As the voltage increases, the time of two stages has the tendency to be equal and even to skip the first stage and

directly be into the second stage.

The droplet internal flows affected by electrical field have a positive impact on improving the evaporation efficiency. It is evident that voltage and concentration increase the velocity of internal circulation considerably. It would benefit for a better understanding and application of charged droplet internal micro electro-hydro Dynamics (EHD) and charged droplet evaporating on solid surfaces.

## Acknowledgements

This research was supported by NSFC 51376084, 51106064 and 51006047. The authors appreciate their support on this work

## References

- Ghasemi, H., & Ward, C. A. (2010). Energy transport by thermocapillary convection during sessile-water-droplet evaporation. *Physical review letters*, 105(13), 136102.
- Dugas, V., Broutin, J., & Souteyrand, E. (2005). Droplet evaporation study applied to DNA chip manufacturing. *Langmuir*, 21(20), 9130-9136.
- Craster, R. V., Matar, O. K., & Sefiane, K. (2009). Pinning, retraction, and terracing of evaporating droplets containing nanoparticles. *Langmuir*, 25(6), 3601-3609.
- Yu, Y. S., Wang, Z., & Zhao, Y. P. (2012). Experimental and theoretical investigations of evaporation of sessile water droplet on hydrophobic surfaces. *Journal of colloid and interface science*, 365(1), 254-259.
- Picknett, R. G., & Bexon, R. (1977). The evaporation of sessile or pendant drops in still air. *Journal of Colloid and Interface Science*, 61(2), 336-350.
- Birdi, K. S., & Vu, D. T. (1993). Wettability and the evaporation rates of fluids from solid surfaces. *Journal of adhesion science and technology*, 7(6), 485-493.
- Shanahan, M. E. R., & Bourges, C. (1994). Effects of evaporation on contact angles on polymer surfaces. *International journal of adhesion and adhesives*, 14(3), 201-205.
- Shin, D. H., Lee, S. H., Choi, C. K., & Retterer, S. (2010). The evaporation and wetting dynamics of sessile water droplets on submicron-scale patterned silicon hydrophobic surfaces. *Journal of Micromechanics and Microengineering*, 20(5), 055021.
- Chen, L., Li, C., van der Vegt, N. F., Auernhammer, G. K., & Bonaccorso, E. (2013). Initial electrospreeding of aqueous electrolyte drops. *Physical review letters*, 110(2), 026103.
- Shanahan, M. E. R., & Bourges, C. (1994). Effects of evaporation on contact angles on polymer surfaces. *International journal of adhesion and adhesives*, 14(3), 201-205.
- Hu, H., & Larson, R. G. (2002). Evaporation of a sessile droplet on a substrate. *The Journal of Physical Chemistry B*, 106(6), 1334-1344.
- Mandal, D. K., & Bakshi, S. (2012). Internal circulation in a single droplet evaporating in a closed chamber. *International Journal of Multiphase Flow*, 42, 42-51.