Analysis of Droplets Spreading on Periodic Plasma Surface

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Abstract. This paper presents the unique spreading process of droplet on dielectric barrier discharge (DBD) actuator periodic plasma surface. High-speed camera is used to capture the droplet spreading process. We use image processing to handle the massive droplets image data. Results show that droplets have more spreading time and much less oscillation cycles on periodic plasma surface, and the spreading diameter is larger while the apex height is lower. Furthermore, the effect of periodic plasma density is studied. And it is revealed that when plasma density increases in certain density range, the maximum and final spreading diameters increase, while the apex height of droplet in stabilization phase decreases.

1. Introduction
High energy elementary of low temperature plasma processes various physicochemical transforma-tions of complex molecules which cannot be done under normal conditions [1], thus provides a considerable prospect for its applications in environmental protection technology.

In recent years, low temperature plasma generated by DBD has been widely used in some aspects of environmental protection, such as toxic gas degradation [2], waste degradation [3]. However, plasma is not adequately applied for sewage treatment, because of lacking knowledge of the mechanism and regularities of the inherent physicochemical processes. The spreading behaviour of droplets impacting on a solid surface is a basic physical process in plasma water treatment, and has a very important role in a wide variety of applications such as spray-cooling, sewerage treatment, micro-fabrication of structured materials [4]. Therefore, it is important to study the kinetic features of droplet impacting on plasma surface.

In this paper, the DBD actuator have been designed to generate periodic electric field in internal side of the droplet impinging area (shown in figure 1), so the plasma streamers could act on the inside part of droplet. A droplet kinetics system is established to study the droplet spreading process on this periodic plasma surface.

2. Experiment details
2.1. Experimental set-up
Figure 1 shows a schematic set-up for the experiment of droplets impacting on the Dielectric Barrier Discharge (DBD) surface. Two syringes are connected by a rubber tube, and droplet syringe uses a 0.16 mm polypropylene needle to generate the same size droplets. The DBD actuator surface is horizontal and the droplet syringe is vertical, their distance is 72 mm. A vertical glass tube is used to protect the
droplets from air flow disturbances. By pushing the control syringe, droplets are formed from the needle of droplet syringe, impact on the surface of the DBD actuator.

![Figure 1. Schematic diagram of experimental set-up.](image)

The DBD actuator is powered by a sine AC power supply to generate periodically distributed plasmas of different densities, as shown in plasma surface of figure 1. We record the entire impact process with a high-speed camera. The camera is horizontal and has a shutter speed of 20,000 frames/s with a resolution of 1064x762 pixels. The spatial resolution (number of pixels per mm) is 67 pixel/mm. The LED light is used to fill the camera and increase the contrast of the droplet image.

Experiments are performed at room temperature and the droplet is deionized water. Other things equal, the maximum spreading diameter and apex height of the droplet are only effected by the droplet’s Weber number [5], the Weber number can be calculated by the following equation:

$$W_e = \frac{v^2 D}{\sigma}$$  \hspace{1cm} (1)

Where $v$ is the impact velocity, $D$ is the droplet diameter, and $\sigma$ is surface tension of the droplet.

Assume that the height difference of droplets is $\Delta H$ in two frame images before impact, the horizontal diameter of the droplet is $D_h$, and the vertical diameter is $D_v$. We can calculate the equivalent diameter $D$ and impact velocity $V$ by the following equation:

$$V = \frac{\Delta H}{t}$$  \hspace{1cm} (2)

$$D = (D_h^2 D_v)^{1/2}$$  \hspace{1cm} (3)

Where $t$ is the interval time of the two frames.

According to equations 1, 2 and 3, we can calculate that the droplets generated by the droplet syringe have an equivalent diameter of 2.053±0.05mm, a droplet impact velocity of 1.194±0.02m/s, and a weber number nears 40. The droplet syringe is able to generate droplets of same size in the error range.
2.2. Image data process

5000 images are obtained in each set of experiment. We need image processing algorithm to calculate spreading diameter and apex height of the droplets. The images, captured by the high-speed camera, have an important feature: the background has not changed much, as shown in figure 2.

![High-speed camera images.](image)

With this feature, we can use the background difference method to extract our droplet targets. The background difference method is a common method for target segmentation extraction in a still scene. It performs a difference operation between the current frame image and the background frame image to get a grayscale image only containing the target region. Target regions are the pixels exceeding a certain threshold. Assuming that $B(x,y)$ denotes the background image pixel, $I(x,y)$ denotes the current image pixel, and the threshold is $T$ (ranging from 0 to 255). The pixel of target region is:

$$f(x,y) = \begin{cases} 
|B(x,y) - I(x,y)|, & \Delta(x,y) > T \\
0, & \Delta(x,y) \leq T 
\end{cases} \quad (4)$$

Where, $\Delta(x,y) = |I(x,y) - B(x,y)|$ if $(x,y)$ denotes the pixel of target region.

We use figure 2a as the background image, and set threshold $T$ to 20. According to equation 4, the target regions of figure 2b, 2c, 2d can be extracted, results are shown in figure 3. Then we can calculate the spreading diameter and apex height of the droplet through pixels.

![Schematic diagram of image data process.](image)

3. Results and discussion

3.1. Effect of periodic plasma

Other things equal, the droplets impact on the DBD actuator surface to study the effect of periodic plasma, with no power supply and a sine AC power supply of 6kv (peak-to-peak), 5khz. We repeat the comparison experiments several times and obtain reproducible results.
According to droplet impinging model [6], droplet impact process usually consists of three different phases: spreading, drop oscillation and stabilization. Figure 4 and 5 show three phases and spreading parameters of the droplet impacting on the DBD actuator surface in two conditions:

3.1.1. Spreading. phase lasts for 3.35ms on the surface without periodic plasma, and the droplet has maximum spreading diameter of 4.567mm. For periodic plasma surface, the droplet experiences a longer spreading time (5.55ms, 1.66 times of the other condition), has a larger maximum spreading diameter (5.284mm, 1.16 times of the other condition).

3.1.2. Oscillating. phase is quite different in these two conditions. The droplet oscillating phase lasts for 187.65ms with 22 cycles (described in figure 5b) of oscillations on none plasma surface. However, it takes just 42.65ms and 4 cycles of oscillations on periodic plasma surface. The droplet viscous dissipation caused by oscillation is significantly reduced, and the surface energy of droplet is more transferred into deformation energy, so that the spreading diameter of droplet is larger on periodic plasma surface.

3.1.3. Stabilization. phase shows an obvious difference of droplet morphology. The droplet on periodic surface has a larger spreading diameter and lower apex height than that on none plasma surface.

3.2. Effect of plasma density
The plasma density increased with the increase in applied voltage [7]. We apply a sine AC power supply of same frequency (5 kHz) and different peak-to-peak voltages (ranging from 4kv to 8kv) to generate different plasma density. Then the spreading behaviour of droplets at different plasma densities is studied.

We repeat the comparison experiments several times and get reproducible results. The spreading diameter and apex height of droplet are compared to examine the effect of plasma density, and results are shown in figure 6.

The maximum and final spreading diameters increase with increasing plasma density, as shown in figure 6a. The effect of plasma density on apex height of droplet is shown in figure 6b. The apex height of droplet at stabilization phase decreases with increasing plasma density.
4. Conclusions
This paper focuses on the process of droplet spreading on the periodic plasma surface. The periodic plasma has an obvious effect on the spreading process of droplets, which shows longer spreading time, much less oscillation times and larger spreading diameter. Also, the density of the periodic plasma has a role in droplet spreading process. The experimental results show that the periodic plasma with higher density produces larger maximum spreading diameter and final spreading diameter, and lower apex height of stabilization phase droplet in certain density range.

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