A Phenomenon Study on Spreading and Evaporating Process of Droplet on DBD Actuator for Wind Turbine Anti-icing

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Abstract. This paper reports on the phenomenon of the unique spreading and evaporation process of water droplets on the surface of a dielectric barrier discharge (DBD) actuator. High-speed photography was used to capture the droplet spreading dynamics, and the temperature field evolution was characterized by infrared imaging. On the DBD actuator, the maximum spreading diameters of the droplets are shown to be increased by ~95%, and the contact angles decrease from 58º to 13º, indicating that the DBD plasma significantly increases the hydrophilicity of the actuator surfaces. It is also revealed that the evaporation time induced by the DBD plasma is 6.54 times faster than that of an electric heater. It is argued that coupled effects of the hydrophilicity caused by plasma and the heat flux in the streamers bridging the electrodes and the droplets should be the crucial points of plasma evaporation physics of impinging water droplets, which are especially meaningful in anti-icing applications.

1. Introduction

Wind energy as a clean and renewable energy has been valued by the world. However, wind turbines installed in high altitudes is facing the most significant threat, that is, ice formation. Reduction in energy output derives from the loss of aerodynamic performance due to the ice on the blades [1]. Ice is also potential hazards to staff in wind power station and passers-by. On the other hand, wind turbines must be switched off to remove the ice in severe ice accumulation for safety, which further reduces the energy production rate [2]. In addition, it may cause vibration and resonance of the blades and other components of the unit to exceed the design fatigue load. Therefore, the anti-icing mechanism on the fan blades is indispensable.

Generally speaking, in terms of anti-icing, there are three categories. (1) Passive method based on antifreeze. This method is derived from aircraft anti-icing, with glycols such as polyhydric alcohols, which can lower the freezing point and prevent icing. However, each time the amount of spraying is large, the retention time of the anti-icing ability is generally not long [3]. More critically, residual chemicals can also be harmful to the environment. (2) Passive method based on super hydrophobic surface. Such surfaces generally reduce the surface water/ice adhesion and allow it to detach before solidifying into ice. However, studies have shown that the surface water/ice adhesion and allow it to detach before solidifying into ice. However, studies have shown that the mechanical strength and chemical stability of superhydrophobic surfaces are not good [4], which means that the anti-ice endurance time needs to be strengthened. Studies have also shown that super-hydrophobic surfaces with roughness are more susceptible to ice adhesion in low temperature and high humidity environments [5]. (3) Active heating methods based on heating, usually using hot air or heating resistors. This method is simple and effective,
but the power consumption problem and the heating efficiency problem are more significant [6], so most of them are only applied to the blade leading edge of the fan blade.

DBD plasma actuator is regarded as a promising anti-icing device due to its enormous thermal effect even in the context of aerodynamic actuators with external flow as thermal takers [7, 8]. Cai et al. [9] conducted anti-icing and de-icing experiments of DBD plasma in an ice wind tunnel, where 5mm ice was completely removed within 150 seconds. Zhou et al. [10] also demonstrated that the power consumption of the DBD plasma devices is similar to the conventional electric heating. However, the possible advantages of a DBD plasma heater is still unclear, and the fundamental behavior of the interactions between the DBD plasma and the impinging water droplets still remain unrevealed. The purpose of this paper is to reveal the phenomenon after the single water droplet impinging the DBD actuator surface, including spreading process and evaporating process, and compared with the resistance heating method. For this purpose, a DBD actuator with an electric heating device attaching on the back is designed to avoid interference from other variables. The high-speed photography and the infrared (IR) temperature imaging results well demonstrate that the DBD plasma could be significantly superior to the electric heating, regarding the dewatering speed and the power density consumption.

2. Experimental

Figure 1 shows the schematic of experimental equipment. It consists of a droplet generator (injector-based PP needle, 0.16mm in diameter) and an image acquisition system with three cameras. Droplets free falling from needle (60mm high) at zero initial velocity, with the equivalent diameter ($D_0$, calculated by [11]) of ~2.01mm and impinging the DBD actuator surface at the velocity ($V_0$) of ~0.75m/s. The side-view image acquired by a high-speed camera (iSpeed 716, iX cameras Inc.) with the speed of 20,000 frames per second (fps), to record the dynamic process of droplet freely falling to the surface of DBD actuator and spreading. The top-view image acquired by a DLSR CCD (D800, Nikon) with the speed of 30fps, to record the dynamic process of droplet evaporating. The temperature is measured by IR Camera (A6700SC, FLIR).

As shown in figure 1, the DBD actuator with an electric heating film is constructed on a 4-layered PCB, the integration of two heating modes (DBD plasma heating, electric heating) is realized. The average temperature of the heating area was equal (91.8ºC) in both modes. In the DBD plasma heating mode, the electrodes AB are connected to the AC source (6.5kV voltage peak-peak, 10kHz frequency) and CDE are grounded, the power density is ~0.10W/mm² (measured from Lissajous-Figure). In the electric heating mode, the heating film is connected to the DC source (1.7V, 4A), the power density is ~0.27W/mm². Due to the dielectric conduction loss in the heating process of the heating film, the true power density will be lower. But it is certain that the power density of DBD plasma heating is at least not higher than that of electric heating.
3. Result and Discussion

3.1. The Spreading Process of a Droplet

According to the droplet spreading model, the droplet goes through four phases [11], droplets in both operation modes follow the model, and show difference dramatically, as shown in Figure 2. In this case, the Reynolds number is $R_e = 1688.099$, Weber number $W_e = \frac{\rho D_o U_0^2 \delta}{\sigma} = 15.663$, the Ohnesorge number $Oh = \sqrt{\frac{\mu}{\rho \sigma D_o}} = 0.0023$, indicating that the viscous force does not play a leading role in the contraction process[13].

![Figure 2. The spreading behavior of droplet in each phase on DBD plasma heating mode (left column) and electric heating mode (right column).](image)

3.1.1. Kinetic Phase. A water droplet in this phase generally lasts $100\mu s$, $t_{kin} \approx 0.1D_o/V_0$ [12], which is further verified in this paper. During the kinetic phase, the droplet taking the shape of a sphere of which the bottom is cut off, has not yet begun to spread, the dominant force in dynamic process is inertia, which is characterized by Oh and We. Hence, as the theory predicts, the droplet behaviour at this stage on both modes is almost identical.

3.1.2. Spreading Phase. During spreading phase, the droplet taking the shape of spherical cap with a liquid film spreading from the bottom, the dominant force is the dynamic pressure of the impact [12], the three-phase line of contact expansion rapidly, so the dynamic advancing contact angle could be relatively big. When the three-phase line of contact stop expanding, the droplet taking the shape of an irregular spherical cap in most cases, the spreading diameter of droplet reaches its maximum, called $\beta_{max}$, which can be bigger than equilibrium conditions. This phase lasts 7.6ms in the DBD plasma heating mode and 3.5ms in the electric heating mode. On the DBD surface, liquid film appeared at the bottom of the contact site at 0.4ms, oscillating wave occurred at 0.6ms, and the oscillating wave made the droplets appear in a small stepped shape at 1.3ms. At 7.7ms, the horizontal radial kinetic energy of the liquid film edge decreased to zero. For the latter case, the droplets appeared at 0.4ms, produced oscillating waves at 1ms, and presented large step-like droplets at 1.6ms. At 3.6ms, the kinetic energy of the horizontal radial direction of the liquid film edge decreased to zero. In summary, by contrast, the droplet in the DBD plasma exhibits longer time (~228%), thinner liquid film (~28%), larger maximum spreading diameter (~195%) and smaller amplitude of oscillation wave.

3.1.3. Relaxation and Oscillation Phase. During this phase, the motion of droplet is a circulation of bounce back and spread, like a damped harmonic motion, and the spreading diameter shows a trend of decreasing. Viscous dissipation is the main reason of the damped interface oscillation, so the final state of the oscillation depends on the receding contact angle and surface tension. In some cases, for example
the complete wetting took place, the receding of spreading diameter would not happen but continue to spread out. This phase lasted 346.4 ms in the electric heating, with droplet experiencing about 45 cycles of oscillations and the amplitude of the height of the droplet, $D_h$, gradually decreasing. The droplet diameter, $D_B$, remains basically unchanged after 4 cycles due to the “pinning effect” [14]. However, the droplet in plasmas lasted 72.3 ms and experienced 2 noticeable oscillations, during which $D_B$ and $D_h$ attenuate. By contrast, $D_h$ in the case of plasmas repeats ~11 times fewer cycles and the peak-to-peak amplitudes are also ~4.5 times smaller than that of the electric heating, indicating that the kinetic energy of the droplets has been mainly relaxed through the radial spreading in plasmas.

3.1.4. Stable Phase. The final droplet shape is determined by the surface tension and the contact angle[13]. In this experiment, the droplet reaches a stable state when the accumulative changes of $D_B$ and $D_h$ are less than 0.01 mm and 0.005 mm in 1 ms, respectively. By contrast, contact angles of the droplet on DBD mode decrease from 58° to 13°, indicating that the DBD plasma significantly increases the hydrophilicity of the actuator surfaces.

3.2. The Evaporating Process of a Droplet
In the 10s after the stable phase, the author observed a completely new phenomenon. Figure 3 shows the characteristic evaporation processes under both modes, and compares the contact area variations. The observations have been repeated more than fifty times to ensure the repeatability of the phenomenon.

3.2.1. On DBD Plasma Heating Mode. During about 8.5 s after the droplet impinging on DBD actuator surface, a unique evaporation phenomenon has been observed, which could be divided into two stages. The secondary spreading stage of the contact area typically lasts 4.4 s in the experiments, and $D_h$ gradually increases, accompanied by the inward suppression on the upper and lower sides. During the process, thin and even “wings-like” liquid film appears on both sides of the droplets. After “wings” appeared, it separated from the main body and quickly evaporated, resulting in a temporary reduction in the spread area, as shown in Figure 3. At 4.4 s, after the maximum contact area, the fragmented evaporation stage typically lasts 4.16 s, during which the droplet is randomly divided into several parts by DBD plasmas, and each part evaporates rapidly. The averaged variation rate of the contact area in the secondary spreading stage is 25.59 mm$^2$/s before the wings-forming criterion, and 10.14 mm$^2$/s afterwards. The evaporation rate is of significant importance in the anti-icing applications, and may be modified by the rate of change of the contact angle[14], resulted from the plasma surface functionalization of hydrophilic enhancement.
3.2.2. On Electric Heating Mode. The spreading dimension of the droplets on the electric heating surfaces is limited. Constant stage typically lasts 41s, during which the droplet height decreases gradually but the contact area keeps constant resulted from the pinning effect [14]. Reduction stage typically lasts 14s, during which the edge of the droplet irregularly shrinks, due to the inhomogeneity of the substrate surface.

3.2.3. The Coupled Effect of Hydrophilicity and Bridging. It has been shown that the water droplet in DBD plasmas evaporates 6.54 times faster than the case of electric heating. Result show that the contact area of droplet on DBD plasma surface is ~3 times bigger than that on normal heating surface, the increase of heat transfer area will inevitably bring the increase of evaporation rate. Beyond that, the average power consumption is less than half for the similar surface temperature, that to say, the underlying physical mechanisms should be different, significantly. Considering the plasma heat flux mainly exists in the streamers bridging the electrodes and the droplets, and the exist of droplet that in the middle of the two discharging loops could be bridging to enhance the strength of discharge including thermal effect. It is argued that coupled effects of the hydrophilicity caused by plasma and the heat flux in the streamers bridging the electrodes and the droplets should be the crucial points of plasma evaporation physics of impinging water droplets.

4. Conclusion
In a conclusion, there are three novel findings in the observations: First, the gross lifespan of a droplet is 6.54 times shorter than that of a common electric heater operated at the same average temperature with 2.7 times lower input power density. Second, the spreading diameter of the droplets is typically 1.95 times larger than that of the controlled cases with little tendency of bouncing; Besides, there is strong evidence for the existence of the secondary spreading process, further stretching the water film. The results may provide new insights in the design of high efficient anti-icing devices for wind turbine.

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