Multiphase Flow and Heat Transfer of Electrospray Droplets for Cooling

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1. Introduction

Electrospray cooling is recently a promising heat removal route for electronics due to its powerful cooling capacity, tiny liquid supply, and precise temperature control. Since first reported in 1882 [1], the electrospray technology has attracted increasing research interests. Fig. 1 shows the typical setup of electrospray, where the capillary nozzle is connected to a high-voltage power supply, thus the supplied liquid is going to breakup into numerous ultrafine droplets with electrodynamic (EHD) forces overcoming surface tension. Nowadays, the relevant applications have been successfully employed in ink-jet printing, industrial dust removal, agricultural plant protection, and meso-scale combustion [2-4].

Previous literatures have confirmed the heat transfer enhancement of electrospray cooling [5-7]. However, the involved multiphase flow characteristics and heat transfer mechanisms are very complicated and still unclear. Specifically, the droplets behaviors of electrospray cooling, such as disintegration, spreading, or evaporation, are quite different from the traditional conditions, which will significantly affect the entire cooling performance.

In this study, the main contribution is to experimentally investigate the impact behaviors and evaporation characteristics of electrospray droplets on hot substrates, as well as the analysis of heat transfer enhancement mechanisms.

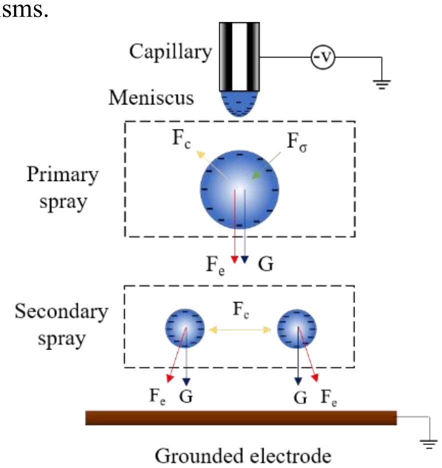

Fig. 1 Schematic of the electrospray formation.

2. Experimental apparatus

The experimental setup of present work in shown in Fig. 2. It consists of the spray generation, spray visualization, and heat transfer measurement parts. Deionized water and ethanol are employed as coolant, and their properties are listed in Table 1. The liquid was supplied to the metal capillary nozzle by syringe pump with certain flow rates. A high voltage power supply (voltage 0-30 kV, current 0-2 mA) was connected to the nozzle, whereas the hot counter substrate was electrically grounded. The backlit shooting was employed for visualization where a LED cold light was placed opposite a high-speed camera. The resolution was about 1024 × 768 pixels, and the frame rate was fixed as 4000 fps.

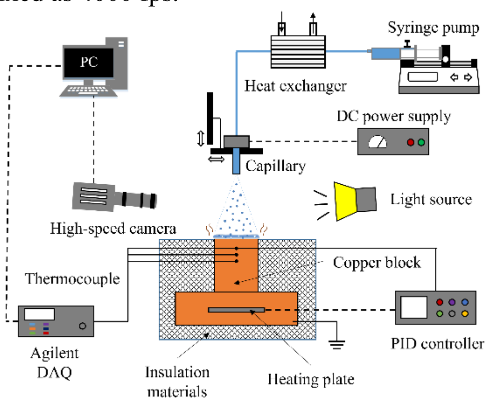

Fig. 2 Experimental setup of elelctrospray cooling.

Table 1 Physical properties of water and ethanol at 25°C.

Fluid	*Water*	*Ethanol*
Density (kg/m^3)	998	789
Viscosity (mPa·s)	1.004	1.074
Surface tension (mN/m)	72	21.97
Electric conductivity (S/m)	1×10^{-6}	5×10^{-5}
Permittivity	78	24.3
Boiling point (°C)	100	78
Specific heat (kJ/kg)	4.18	2.48
Latent heat (kJ/kg)	2443.6	837.36

3. Results and discussion

Fig. 3 shows the effects of electric field intensity on the electrospray morphology of ethanol. The spray would successively experience the so-called dropwise, micro-dripping, cone-jet, and multi-jet modes with the applied voltage increasing to 6.5 kV. From dropwise to multi-jet, the liquid was found to disintegrate more completely and would cover greater area.

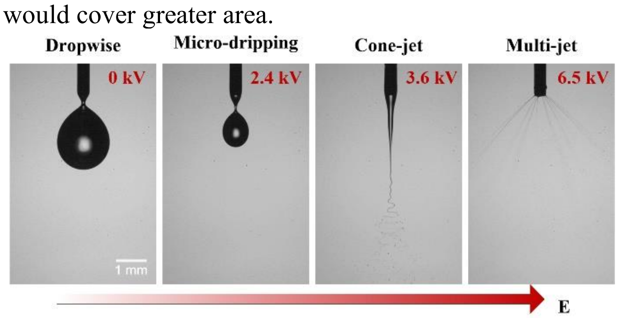

Fig. 3 Electrospray mode evolution using ethanol.

As shown in Fig. 4, the droplet size decreased significantly to approximately several micrometers for multi-jet mode. In addition, the impingement of spray droplet to the substrate was accelerated with a maximum velocity of about 8 m/s by the electric force.

Fig. 5 shows the spray droplets behavior on an overheated substrate at about 150°C. The Leidenfrost phenomenon was clearly observed for the neutral and weakly charged conditions [8]. However, the droplet rebound would disappear for multi-jet mode, and only very thin liquid film could be found. It is mainly attributed the small droplet size and high impact velocity, which makes the impact become very fast, and few charges will escape to the substrate.

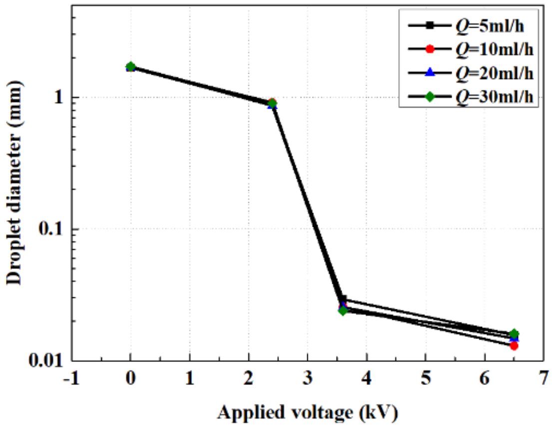

Fig. 4 Droplet diameter of different electrospray modes.

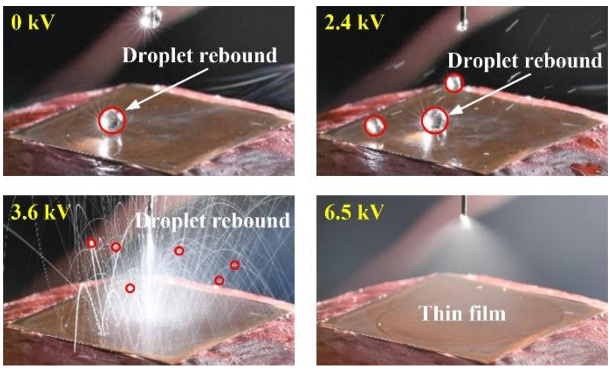

Fig. 5 Dynamic behaviors of electrospray ethanol droplets on overheated substrate at 150°C.

Droplet impact is the main heat transfer way for spray cooling. Owing to the applied electric field, the droplet impact dynamics of electrospray will differ from traditional spray cooling process. Fig. 6 compares the impact morphology of neutral and charged droplets. The results showed that the charged droplet would have a bigger maximum spreading but a smaller maximum recoiling height. In other words, the spreading of impact droplet would be promoted whereas the recoiling would be suppressed for charged droplets. At present, this is primarily attributed to the surface tension weakening effects caused by the surface free charges.

The spreading coefficient β is defined as the instantaneous wetted diameter on the substrate to the initial droplet size. The maximum spreading coefficient β_{max} is of great significance to droplet impact heat transfer. In this study, the correlations of the maximum spreading coefficient of charged droplets were established by applying the Buckingham PI method. The results are shown in Fig. 7, of the the prediction uncertainty is within 5%. In addition, it showed good agreements with experimental results reported in the previous literature [9].

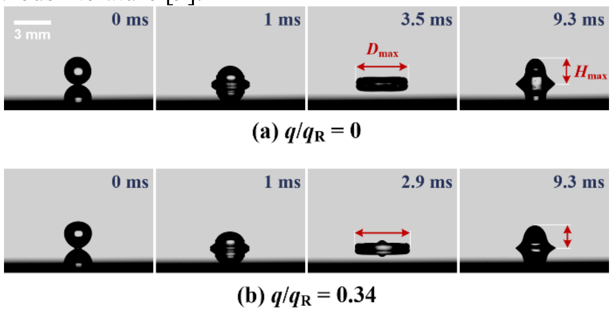

Fig. 6 Snapshots of (a) neutral and (b) charged water droplets impact on substrate.

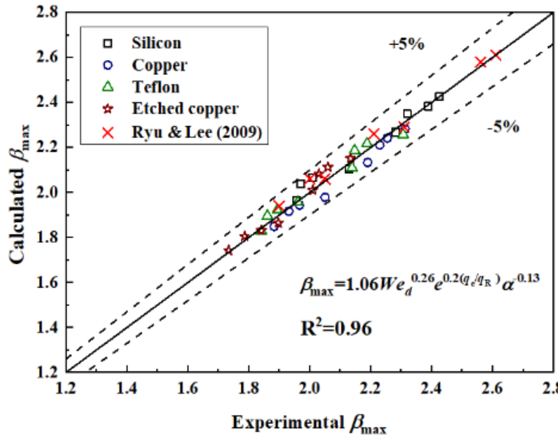

Fig. 7 Prediction of the maximum spreading ratio of charged droplet on different substrates.

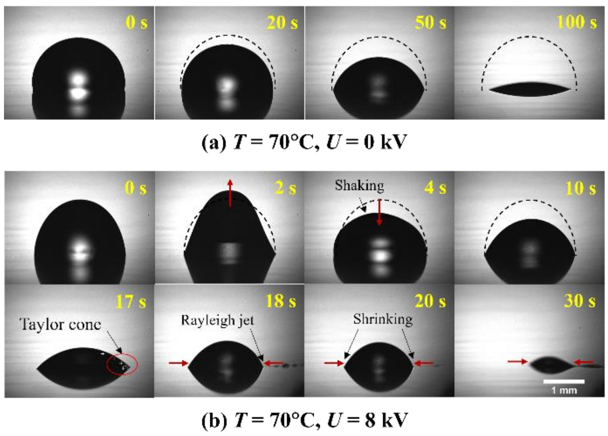

Fig. 8 Snapshots of sessile water droplet evaporation under (a) no electric field and (b) an 8 kV applied voltage.

Sessile droplet evaporation on hot substrate is crucial to the high heat flux of electrospray cooling in the single phase region. Fig. 8 shows the evaporation snapshots of sessile water droplet on hot copper substrates under a needle-to-plate electric field. The total evaporation time is decreased from 111 s to about 34 s with an 8 kV applied voltage. Note that, the droplet-air interface would experience dramatic evolution, such as shaking, tiny ejection, or shrinking. The results from Fig. 9 show that both the increase in substrate temperature and electric field intensity would enhance the droplet evaporation of sessile droplets.

Theoretically, this enhancement mechanism of non-uniform electric field on droplet evaporation was basically attributed to the combined effects of corona wind blowing, surface tension weakening, and molecular orienting.

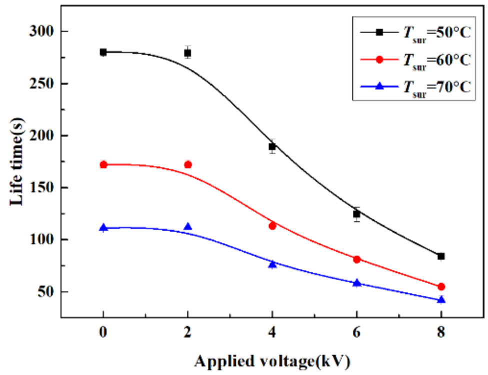

Fig. 9 Sessile droplet evaporation time with different substrate temperatures and applied voltages.

4. Conclusions

In summary, the impact dynamics and heat transfer of electrospray droplets were experimentally investigated in this work. The electrospray mode would vary with the applied electric field intensity and flow rate. The visualization results showed that the maximum spreading coefficient was proportional to the charge density of the impact droplet, which increased up to about 9.6% compared to neutral droplets. A prediction model of the maximum spreading ratio based on the impact velocity, droplet charge density, and substrate wettability was eventually established. In addition, the evaporation of sessile droplets under a needle-to-plate electric field was found dramatically accelerated. With increasing electric field intensity, the “depinning” and “tiny jet” phenomena near the three-phase contact line could be observed, accompanied by an extra constant contact angle (CCA) evaporation stage. As a result, the evaporation rate increased by about 6.8 times over the traditional condition. This work was expected to a better understanding of the electrospray cooling technique and demonstrate an efficient way for high heat flux dissipation.

Acknowledgment

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