



Heat transfer performance of water-based electrospray cooling

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ABSTRACT

Electrospray (ES) cooling is a promising technique for dissipating high heat fluxes due to its excellent heat transfer characteristics and high energy efficiency. Conventional sprays exhibit a low efficiency due to droplet rebound and require a high pumping power. These issues are resolved with electrospraying, in which fine droplets are dispersed and accelerated with an electric field, thereby improving the cooling efficiency with a relatively lower pumping power and a low overall system weight. In this study, we investigate the thermal performance of ES cooling with water as the working fluid using a single stainless-steel nozzle with an inner diameter $D_i = 410 \mu\text{m}$. We use three different flow rates, $Q = 200, 400$, and $600 \mu\text{L/min}$, with a wide range of applied ES potentials, $V_1 = 0\text{--}7 \text{ kV}$, to investigate various ES modes. The results show that an increase in the applied ES potential can improve the heat transfer performance by 12.58% and 6.65% in the single-phase and transition regions, respectively, while the improvement is insignificant in the nucleate boiling region and at the critical heat flux. The variations in the ES mode are examined in detail using sequential optical images captured by a high-speed camera. Dimensionless correlations for each cooling regime are proposed using the Weber, electric Weber, and modified boiling numbers. These correlations provide good predictions of the heat transfer performance for all applied ES potentials and flow rates with an overall mean absolute error of 2.96%.

1. Introduction

The continuous miniaturization of electronic devices is accompanied by an increase in the thermal design power (TDP), which is a major challenge for the performance and reliability of these devices. Recent advances in materials and microfabrication technologies have facilitated the development of innovative cooling schemes such as mini-/microchannel heat sinks [1], jet impingement [2], porous materials [3], nanofluids [4], phase-change materials [5], thermoelectric coolers [6], three-dimensional (3D) manifold microchannels [7], and hybrid cooling schemes [8], which exhibit significantly higher thermal management performance compared to that for conventional cooling. In particular, two-phase spray cooling has demonstrated great potential for high heat flux applications due to its superior heat dissipation capability originating from the large liquid–vapor interface area, the spatial temperature uniformity due to the use of multiple nozzles, and the temporal isothermality near the onset of boiling (ONB) [9,10]. Despite these advantages, its applications in the electronics field have been restricted owing to some challenges, including the requirements of

a large pumping power and small filter and its systematic complexity [10]. Particularly, the high pressure required to break the liquid into fine droplets decreases its energy efficiency.

Electrospraying is an atomization technique that does not present the disadvantages of conventional spray techniques. In this technique, an electric field ionizes the conductive liquid flowing through a nozzle, enhancing the intermolecular electrostatic repulsion that induces electric stress on the interface [11,12]. Accordingly, the liquid surface at the tip of the nozzle is deformed to a conical shape and disintegrates into fine droplets, subjected to the electrostatic force, surface tension, hydrostatic pressure, and inertial force. Due to this process, an electrospray requires negligible pressure and pumping power to maintain the spray, as compared to conventional sprays. Consequently, it has replaced conventional spraying in a wide range of applications such as encapsulation and emulsion [13], the creation of thin films [14], fuel injection [15], fine particle collection [16], and mass spectrometry [17]. As electrospraying generates various spray modes with a high energy efficiency, it is a very promising cooling technique for high-power electronics. Feng and Bryan [18] investigated the heat transfer

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Nomenclature

Bo^*	modified boiling number
CHF	critical heat flux
D_i	inner diameter
H_1	nozzle-to-extractor distance
H_2	extractor-to-ground distance
h	convective heat transfer coefficient
h_{fg}	latent heat
k	thermal conductivity
L	square heater length
MAE	mean absolute error
Nu	Nusselt number
P	heater power
Q	volumetric flow rate
q''	heat flux
R''	total thermal resistance
T	temperature
ΔT	temperature difference
V	velocity
ΔV_1	applied ES potential difference between the nozzle and the

	extractor
ΔV_2	applied ES potential difference between the extractor and ground
We	Weber number
We_e	electric Weber number

Greek symbols

ε	permittivity
μ	dynamic viscosity
ρ	density
σ	surface tension

Subscripts

exp	experiment
f	fluid, liquid
heater	heater
in	inlet
pred	prediction
s	surface of the ground electrode

characteristics of electrospraying using ethanol for different flow rates, electrospray (ES) potentials, nozzle materials, spacings between the nozzle and the ground electrode, and heated surface structures. They reported that the heat transfer is enhanced with the increase in the applied ES potential owing to the increase in the momentum of the liquid droplets. They also found that thick liquid films created by the high flow rate and high vapor momenta at a high heat flux reduced this enhancement in heat transfer. Deng and Gomez [19] observed that the droplets rebounded less on the heated surface owing to the image force with a sufficient charge relaxation time. Further, it was observed that the two-phase flow regime starts at a relatively lower temperature compared to that in conventional spraying, as reported by Kim [9]. Here, the droplet size was tuned by controlling its electrical conductivity, which resulted in an enhancement in heat transfer. Wang and

Memishev [20] developed empirical correlations for the heat transfer with different nozzle diameters and arrangements in a multijet ES. Gibbons and Robinson [21,22] investigated the local heat transfer characteristics in the cone-jet regime with various flow rates, separation heights, and nozzle diameters.

However, there have been relatively fewer studies on the heat transfer performance of ES cooling than on conventional spray cooling, and all of them have used either ethanol or methanol as the working fluid because of their suitability for electrospraying [19,23]. The properties of water render it difficult to maintain a stable electrospraying mode. Firstly, owing to its high surface tension, maintaining a stable ES mode with water requires much higher applied potentials, which may cause coronal discharge [24,25]. Secondly, because the high electrical conductivity of water leads to a relatively short charge

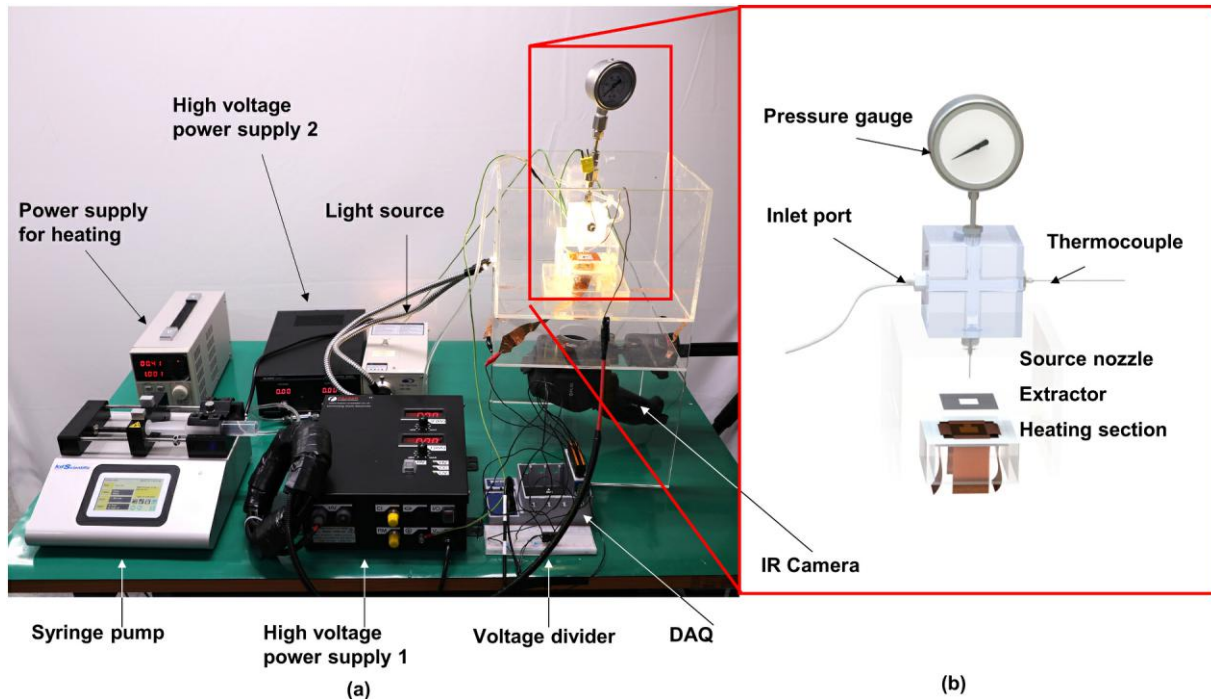


Fig. 1. (a) Experimental setup for measuring the heat transfer performance of electrosprays and (b) a schematic of the electrospray module.

relaxation time, it is difficult to apply appropriate electrical stress on the liquid droplets [26]. Moreover, according to Ku and Kim [27], most experiments considering electrospraying have focused on inviscid or moderately viscous liquids because a stable cone-jet mode is relatively difficult to obtain for highly viscous liquids such as water, and their anomalous behavior cannot be predicted from the results of studies on inviscid liquids. However, since water ES is of particular interest due to its low cost, environment-friendliness, biocompatibility, and desirable properties for cooling, there is a clear need for research on water ES cooling in various domains such as economical metal extraction [28], material preparation [29], desalination by evaporation [30], economical coating and printing [14,31], bio-applications [32], and high heat flux electronics cooling [33]. Therefore, here we investigate the heat transfer performance of electrospray cooling using water as the working fluid. First, we explore the influence of applied potentials on water electrospray modes using high-speed sequential images and determine a suitable applied potential range for spray cooling, while preventing corona discharge. We also report the thermal and hydraulic characteristics for associated electrospray modes at different applied potentials and flow rates. A new prediction model for water-based electrospray cooling is proposed, and this model and experimental data are quantitatively compared.

2. Experimental methods

2.1. Experimental apparatus

2.1.1. Flow loop facility

Fig. 1 shows the experimental system for measuring the heat transfer characteristics of ES cooling. The entire facility consists of (i) a flow loop, (ii) an ES module, and (iii) a test chamber. In the flow loop, deionized (DI) water prefiltered by a 0.22- μm filter (Arioso Power I + 70) is used as the working fluid, and it is introduced into the ES module (Fig. 1(b)) by a syringe pump (KD Scientific, Legato 200), followed by a 90- μm filter to prevent clogging of the nozzle when the test

section is installed into the flow loop. The fluid temperature and pressure are measured before electrospraying using a K-type thermocouple and an oil-filled pressure gauge, which are installed on a $5 \times 5 \times 5 \text{ cm}^3$ polycarbonate block. A stainless-steel needle with an inner diameter $D_i = 410 \text{ }\mu\text{m}$ and a thickness of 135 μm (Luer Lock 22G), which is inserted from the bottom surface of the block, is used for spraying.

2.1.2. Electrospray system

Fig. 2 shows a schematic of the three-electrode ES system consisting of a nozzle, an extractor, and a ground electrode. The electric potential difference and the distance between the nozzle and the extractor are denoted by ΔV_1 and H_1 , and those between the extractor and the ground electrode are denoted by ΔV_2 and H_2 , respectively. Here, ΔV_1 and H_1 mainly determine the ES mode by deforming the liquid interface. As the electrostatic force is inversely proportional to the distance, the extractor enables the cone-jet mode to be achieved at a smaller ΔV_1 and reduces the risk of corona discharge [34]. Thus, a 200- μm -thick aluminum foil extractor with a $12 \times 12 \text{ mm}^2$ square opening is employed to reduce the distance between electrodes. After passing through the extractor, the droplets reach the ground electrode owing to the attractive electrostatic force generated by ΔV_2 . In this study, fixed spacings of $H_1 = 3 \text{ mm}$ and $H_2 = 17 \text{ mm}$ have been used. The stainless-steel needle is connected to a high-voltage direct-current (DC) power supply (Fraser 7360P) to set ΔV_1 . A 200- μm -thick aluminum foil is used as the extractor, which is connected to another DC power supply for ΔV_2 (MK Power, MK 5001-1). Both the voltage sources (ΔV_1 and ΔV_2) are electrically connected to a $10 \times 10 \text{ mm}^2$ thin-film titanium/gold (10 nm/100 nm) electrode, which is deposited on the top of a silicon substrate (114.7 W/mK at 373 K [35]) by electron-beam evaporation. The dimensions of the silicon substrate used in this study are $25 \times 35 \text{ mm}^2$ with a thickness of 525 μm . A thin-film titanium/gold (10 nm/100 nm) heater with a 500-nm thick SiO_2 electrical insulation layer is fabricated on the opposite side of the silicon substrate to supply heat during the experiment. The thin-film heater is powered using a DC

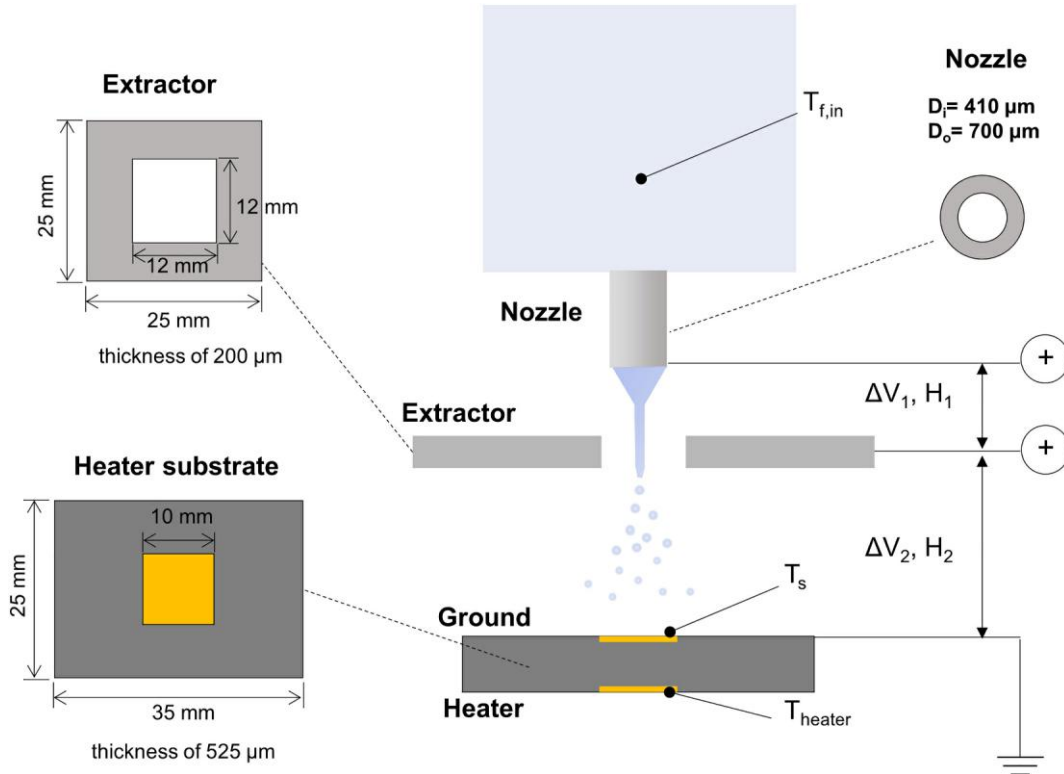


Fig. 2. Schematic of the electrospray system.

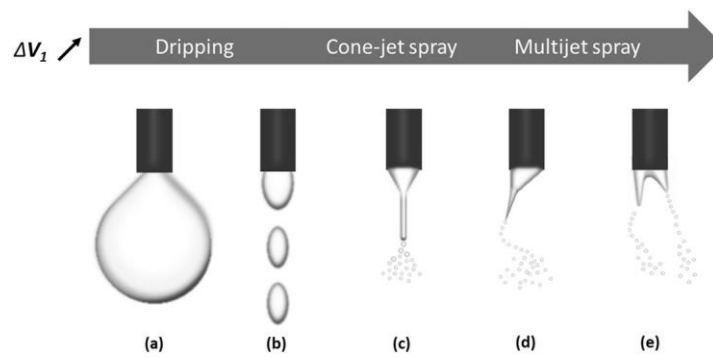


Fig. 3. Schematic of the electro spray modes, where the electro spray potential (ΔV_1) is sequentially increasing from left to right.

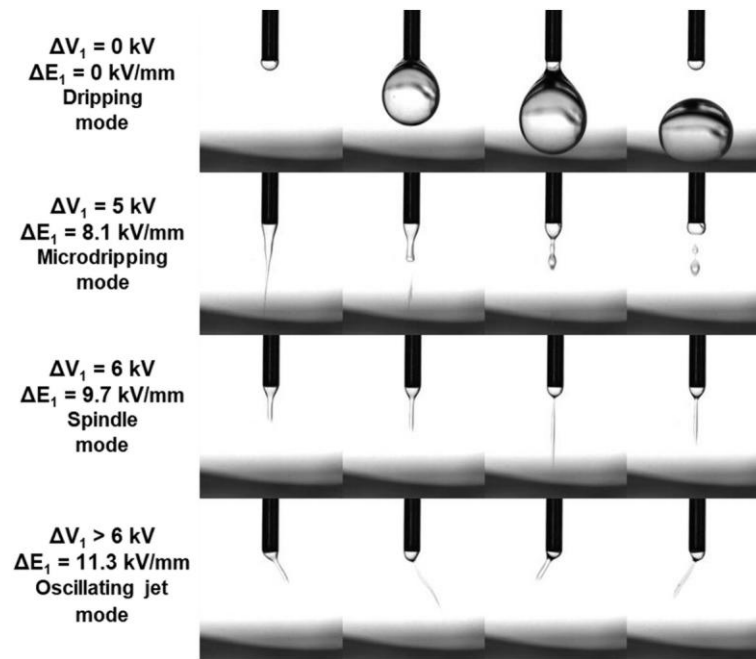


Fig. 4. Sequential optical images of electro spray modes at $Q = 600 \mu\text{L}/\text{min}$.

power supply (MK Power, 3010D). The total input power of the heater is measured using a customized voltage divider consisting of two resistors with high resistances ($47 \text{ k}\Omega \pm 0.1\% + 3 \text{ k}\Omega \pm 0.1\%$) for voltage measurement and a low-resistance shunt resistor ($0.05 \Omega \pm 0.5\%$) for sensing the current. The two voltages (ΔV_1 and ΔV_2) are measured at a frequency of 1-kHz using a data acquisition (DAQ) system (National Instruments, NI-9174). The temperature distribution of the heater surface was acquired using an infrared (IR) thermal imaging camera (FLIR E75) with a resolution of 640×480 pixels. A high-speed camera (Photron FASTCAM Mini UX100) was used to obtain optical images of the ES modes with a resolution of 1280×1024 pixels and a frequency of 2000 fps.

2.2. Test procedure, operating conditions, and measurement uncertainty

The heat transfer characteristics of the ES were measured for three different flow rates of 200, 400, and $600 \mu\text{L}/\text{min}$ at an ambient inlet temperature $T_{f,in} \sim 20^\circ\text{C}$. We used $\Delta V_1 = 0\text{--}7 \text{ kV}$ with a constant ΔV_2 of 0.5 kV to investigate the effect of the flow rate and ES potential difference on the ES modes and corresponding heat transfer performance. The heat flux applied to the heater was up to $37 \text{ W}/\text{cm}^2$.

During the experiment, we first set the flow rate to the desired values using the syringe pump. Subsequently, ΔV_1 and ΔV_2 were applied to the nozzle and extractor to obtain the appropriate ES mode. After the

ES mode stabilized, the DC power supply was used to drive the heater to achieve the desired operating conditions. Once the surface temperature achieved steady-state conditions, it was recorded for 40 s using the IR camera. Then, the input power of the heater was increased in intervals of 1–2 W, and the measurement was repeated until the critical heat flux was reached.

The measurement error in the temperature obtained by the IR camera was $\pm 2^\circ\text{C}$. The uncertainties in the three resistances in the voltage divider were $\pm 0.5\%$, $\pm 0.1\%$, $\pm 0.1\%$. The final uncertainties in the input power of the heater and the average heat transfer coefficient were $\pm 0.53\%$ and 6.7% , respectively.

3. Results and discussion

3.1. Visualization of the electro spray modes

Fig. 3 shows a schematic of the typical ES mode transition with successive increases in ΔV_1 . For $\Delta V_1 = 0$, a large spherical meniscus is formed at the tip of the nozzle because the surface tension is dominant (Fig. 3(a)). Once the gravitational force exceeds the surface tension owing to liquid accumulation at the tip, the droplet releases and impacts the heated surface [36,37]. As ΔV_1 increases, the droplet shrinks with an elongated shape and a higher impact frequency because the electrical pressure acting on the liquid surface tip increases, which

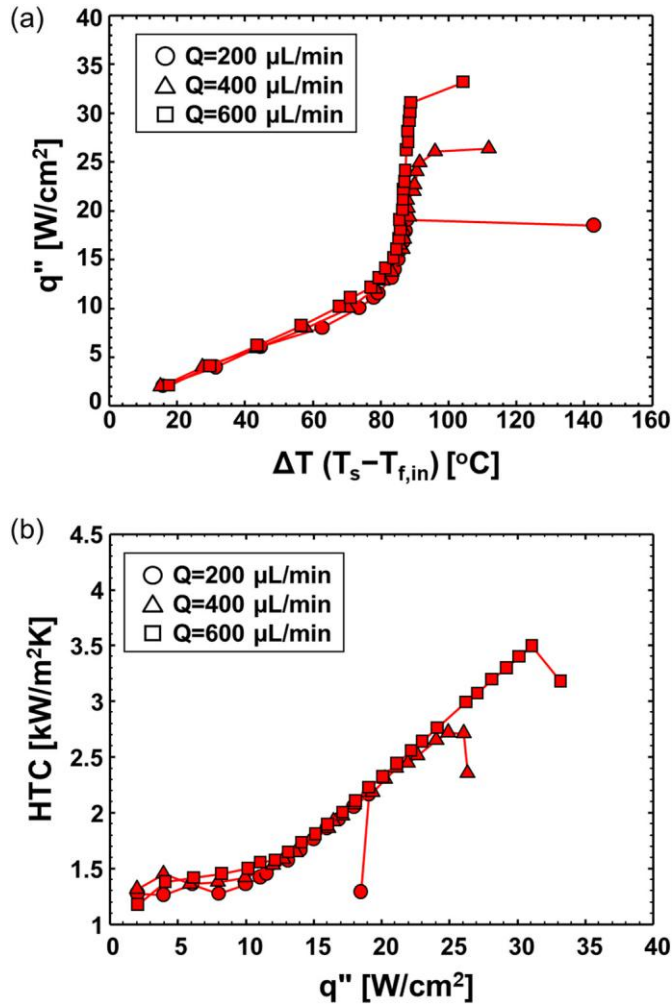


Fig. 5. Heat transfer characteristics of a spray in the absence of an applied ES potential: (a) boiling curves and (b) heat transfer coefficients for different volumetric flow rates.

increases the electric stress and reduces the surface tension force (Fig. 3(b)) [38]. As ΔV_1 increases further, a sufficient electrical stress that overcomes the surface tension and gravitational force is generated, resulting in the formation of a conical shape (Taylor cone) at the tip of the nozzle (Fig. 3c) [39]. In this mode, the fluid particles are primarily accelerated by the electrical stress; thus, they erupt in the form of a jet at the tip of the cone (cone-jet). Once a cone-jet is formed, droplets are created either directly from the tip of the cone-jet or from a filament, which is a long string-shaped droplet detached from the cone-jet.

If the electric charge in the liquid droplet exceeds the Rayleigh stability limit, which is the maximum amount of charge on a finite surface, the droplet starts to break and self-disperses into small-sized droplets to maintain the charge below the Rayleigh limit (ES mode). As ΔV_1 further increases, droplets are broken into smaller droplets. When $\Delta V_1 \sim 7$ kV, the Taylor cone begins to oscillate and tilt owing to the impulse charge (Fig. 3(d)) [37,40], and multiple filaments are generated from multiple jets for $\Delta V_1 > 7$ kV (Fig. 3(e)).

Fig. 4 shows a sequence of the optical images of ES modes at $Q = 600$ $\mu\text{L/min}$, where ΔV_1 varied from 0 to 7 kV. No significant differences were observed for other flow rates, except that relatively smaller droplets were observed for $Q = 600$ $\mu\text{L/min}$ in the dripping mode. Similar to Fig. 3, the dripping mode was formed at low ES potentials and a Taylor cone shape was exhibited at $\Delta V_1 \sim 6$ kV. The Taylor cone was unstable and briefly observed, and it soon changed to the oscillating jet spray mode at $\Delta V_1 \geq 6$ kV. This allowed the system to

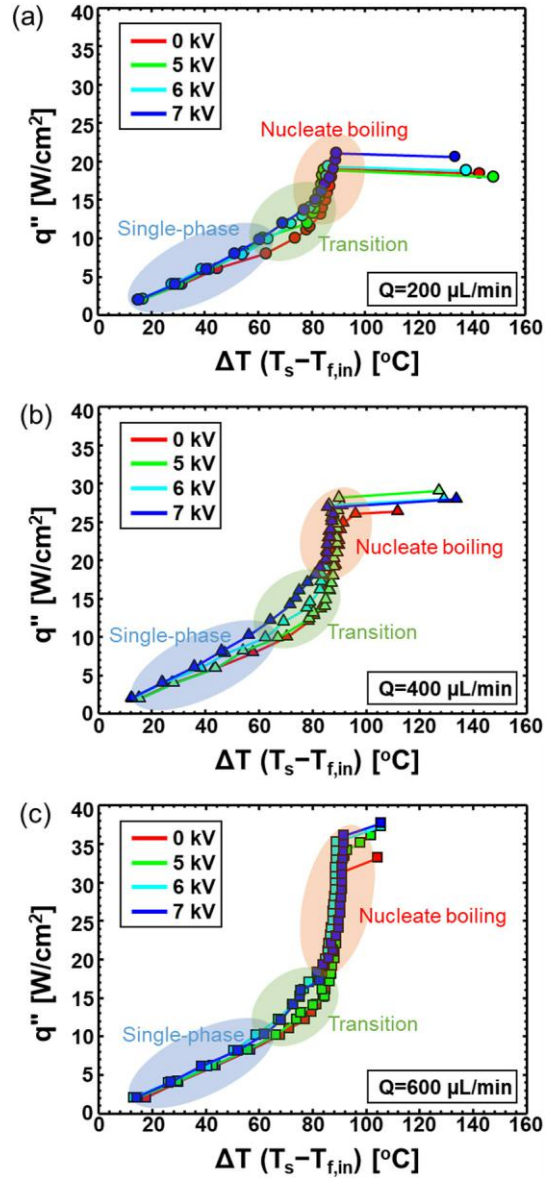


Fig. 6. Boiling curves for different applied ES potentials (ΔV_1) at different volumetric flow rates Q : (a) 200, (b) 400, and (c) 600 $\mu\text{L/min}$.

produce fine droplets compared with those produced in the ES modes without Taylor cone [32,41].

3.2. Heat transfer characteristics

Fig. 5 shows the boiling curves and corresponding convective heat transfer coefficients at three different flow rates $Q = 200, 400$, and 600 $\mu\text{L/min}$ in the absence of an applied ES potential. It is evident that the boiling curve exhibits different slopes as the heat input increases because the cooling mechanisms change. If the heat flux applied to the heater is not sufficient to evaporate all of the droplets, they accumulate on the heater and form a liquid film. In this state, the heat transfer performance is mainly determined by the flow interaction between the droplets and the liquid film. In the single-phase region, convection within the liquid film is promoted by droplet impact [9]. No significant difference is observed for the tested range of $Q = 200$ – 600 $\mu\text{L/min}$ because the flow rate is very small; therefore, the size of an impacting droplet is only determined from the gravitational force and surface tension. As the heat input increases, the latent heat transfer increases, resulting in an enhancement in heat transfer; therefore, the slope of the

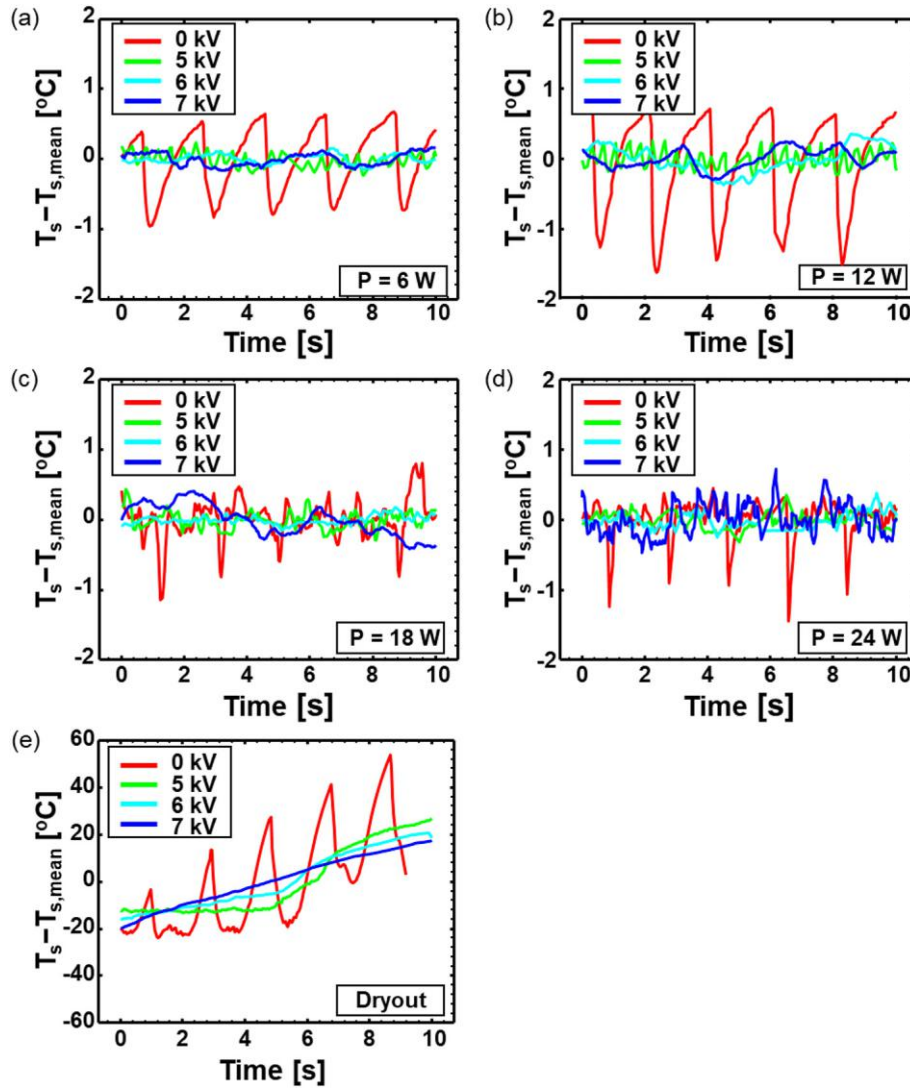


Fig. 7. Temporal variation in the difference between the instantaneous temperature and the time-averaged temperature of the heater surface for different applied powers: (a) 6, (b) 12, (c) 18, and (d) 24 W. (e) Dryout at 400 $\mu\text{L}/\text{min}$.

boiling curve becomes steeper. As the heat flux increases further, the evaporation rate exceeds the flow rate, which causes the incipience of dryout, and the critical heat flux (CHF) is attained. A higher CHF is observed at higher flow rates owing to the increase in the sensible and latent heats, which is consistent with earlier studies reviewed in [10].

Fig. 6 shows the boiling curves at three different flow rates of 200, 400, and 600 $\mu\text{L}/\text{min}$ with $\Delta V_1 = 0, 5, 6$, and 7 kV. Here, the curves corresponding to $\Delta V_1 > 7$ kV are intentionally removed because most of the droplets are dispersed outside the heated area; thus, it is difficult to accurately calibrate the heat transfer performance. Here, ΔT is the difference between the surface temperature at the ground electrode (T_s) and the inlet fluid temperature ($T_{f,in}$), where the temperature drop due to conduction within the silicon substrate is taken into consideration. From Fig. 6, it is evident that the increase in ΔV_1 in the single-phase region reduces the wall temperature. This can be attributed to the different droplet sizes and collision frequencies of electrospray modes, which significantly affects the convective heat transfer. The relatively larger and slow-speed droplets at low ΔV_1 lead to a higher wall temperature at the same heater power, whereas the finer and high-speed droplets at a higher ΔV_1 exhibit a lower wall temperature. As the temperature increases with the increasing heater power, the evaporation rate increases at the liquid–vapor interface owing to the higher interfacial temperature (transition region). In this region, the total

thermal resistance decreases in comparison to that in the single-phase regime as the effective heat transfer rate increases due to partial boiling on the heated surface. In the nucleate boiling region, there is no noticeable temperature change with the variation in ΔV_1 because the heat transfer mechanism is dominated by bubble departure and liquid refreshment within the liquid film. Thus, the effect of droplet impact on the liquid–vapor interface is relatively insignificant.

Fig. 7 shows the temporal variation in the difference between the instantaneous temperature and the time-averaged temperature of the heater surface. Temperature was averaged over the experimental period of 10 s. For relatively low potentials of $\Delta V_1 \leq 5$ kV (dripping mode), there are sudden temperature drops whenever liquid droplets impact the heated surface. Subsequently, the temperature increases until the next droplet impact owing to the sensible heat transfer of the liquid droplet, and these temperature variations become larger and faster as the input power of the heater increases. However, for higher potentials of $\Delta V_1 = 6\text{--}7$ kV (spindle and oscillating jet), these temperature fluctuations are negated because relatively small droplets are frequently sprayed on the heated surface within a short time interval. Thus, a temporal temperature with a higher uniformity is attained.

Fig. 8 shows the variation in the total thermal resistance for $\Delta V_1 = 0\text{--}7$ kV. The total thermal resistance, R'' ($\text{m}^2\text{K}/\text{W}$), is governed by the heater's input power, conduction within the silicon substrate,

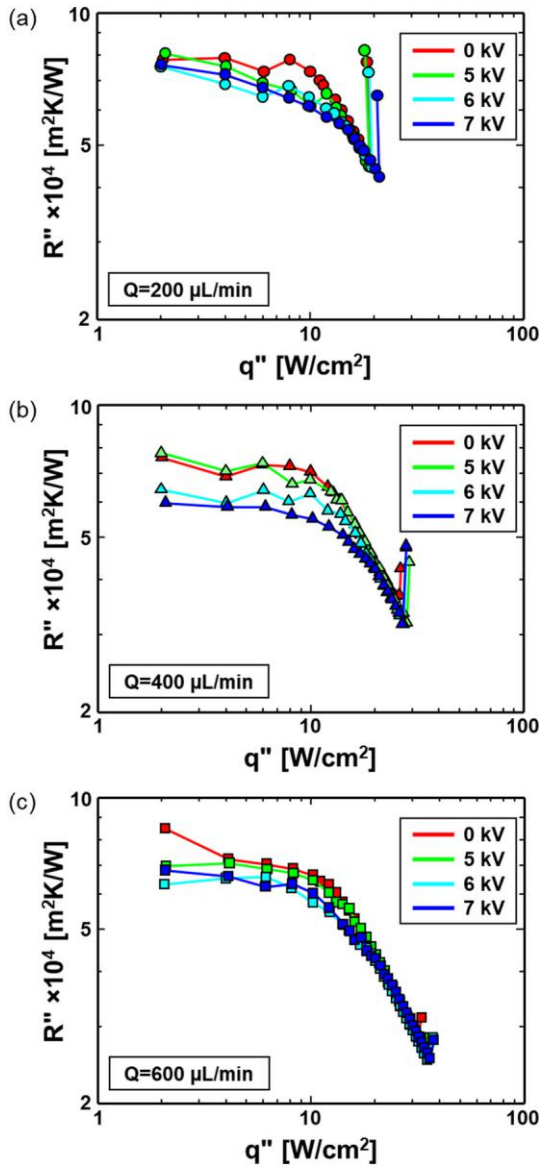


Fig. 8. Total thermal resistance for $\Delta V_1 = 0-7$ kV at different volumetric flow rates Q : (a) 200, (b) 400, and (c) 600 μL/min.

and convection by spray cooling:

$$R'' = \frac{\Delta T}{q''} = \frac{T_s - T_{f,in}}{q''}. \quad (1)$$

As Q increases from 200 μL/min to 600 μL/min, R'' decreases owing to the increase in convective heat transfer, but the variation is small owing to the low fluid velocity. The decrease in R'' becomes more evident when ΔV_1 increases in the single-phase and transition regions. R'' is reduced by approximately 10.65% and 5.99% in the single-phase and transition regions, respectively. There is no significant difference in the nucleate boiling regions since the heat transfer in this region is dominated by the phase change of the liquid rather than by convective heat transfer. Further, the variation in ΔV_1 does not affect the CHF.

3.3. New prediction model

Now, we develop a predictive model for the heat transfer performance of water-based ES cooling. As mentioned earlier in the discussion of Fig. 5, because the heat transfer of the spray is related to the flow rate and heater's input power, we first calculate the Nusselt

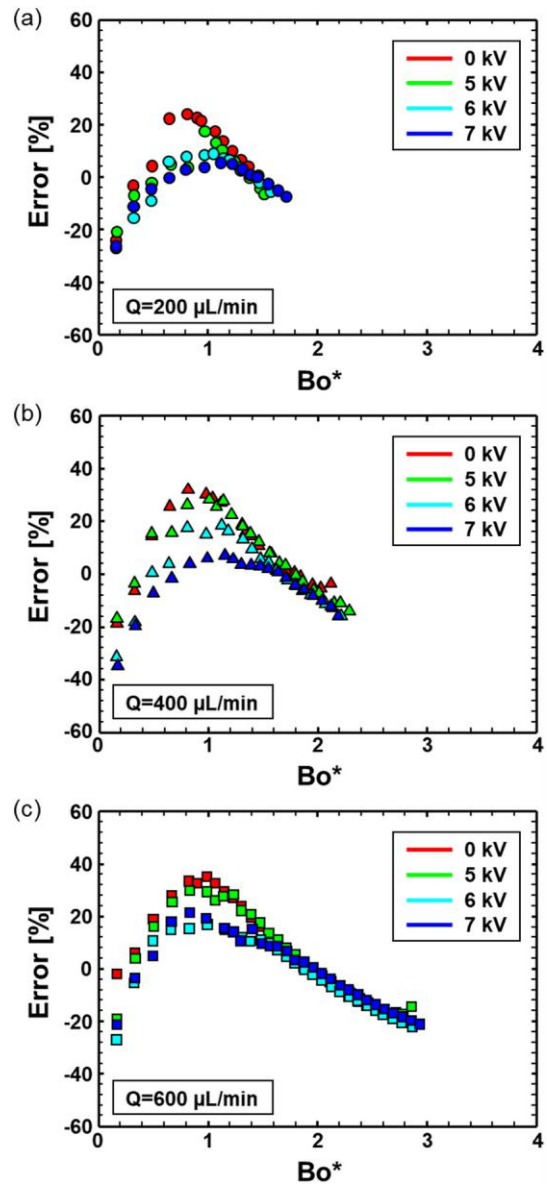


Fig. 9. Variation in the mean error as a function of the modified boiling number at different volumetric flow rates Q : (a) 200, (b) 400, and (c) 600 μL/min.

number in the absence of an applied ES potential ($\Delta V_1 = 0$) using fractional functions of the Weber number (We) and modified boiling number (Bo^*) as.

$$Nu = 174.63 We^{0.073} Bo^{*0.35}, \quad (2)$$

where

$$h = \frac{q''}{T_s - T_{f,in}}, \quad (3a)$$

$$Nu = \frac{hL}{k_f}, \quad (3b)$$

$$We = \frac{\rho_f V^2 D_i}{\sigma}, \quad (3c)$$

$$Bo^* = \frac{q'' D_i}{\mu_f h_{fg}}. \quad (3d)$$

ρ_f is the density of water, σ is the surface tension, μ_f is the dynamic viscosity, h_{fg} is the latent heat of water at the inlet temperature, V is the

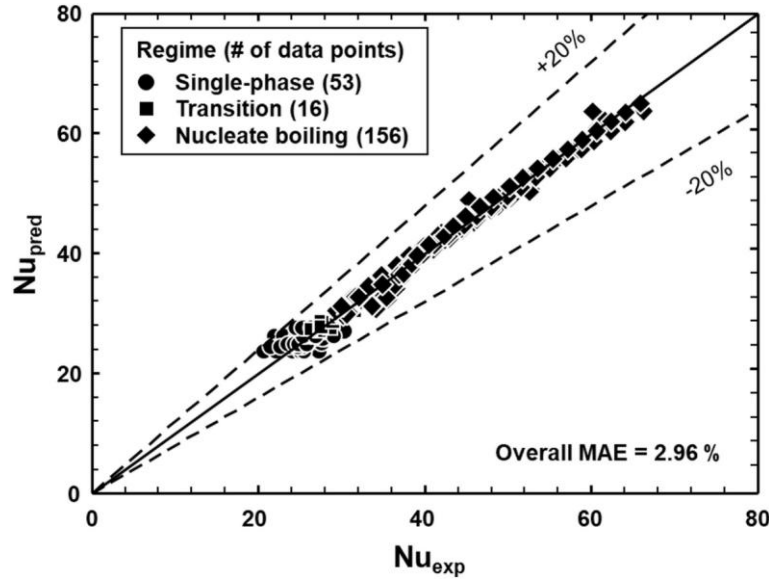


Fig. 10. Comparison of the experimentally determined Nusselt number with that predicted using the proposed correlations.

velocity at the nozzle, and q'' is the total heat input to the heater. The boiling number (Bo^*) is usually expressed in terms of the Sauter mean diameter (d_{32}), but we have replaced it with D_i because it is difficult to characterize d_{32} [42].

Fig. 9 shows the mean error between the experimentally obtained Nusselt number and that obtained using Eq. (2). The mean error is expressed as follows:

$$Error = \frac{Nu_{exp} - Nu_{pred}}{Nu_{exp}} \times 100(\%). \quad (4)$$

It is evident in Fig. 9 that the slope changes near $Bo^* = 0.02$. This is because the dominant heat transfer mechanism is convective heat transfer for $Bo^* < 0.02$, while it is nucleate boiling for $Bo^* > 0.02$. The variations in the error as a function of ΔV_1 are larger in the single-phase and transition regions, while they are not significant for large Bo^* . This can be attributed to the fact that the applied ES potential has a stronger effect on the heat transfer performance in the region dominated by convective heat transfer, and it is less effective in the nucleate boiling region, as mentioned above. Therefore, we propose predictive correlations for the 1) single-phase, 2) transition, and 3) nucleate boiling regions:

Single-phase region:

$$Nu = 9.92 We_e^{0.021} We_e^{0.15} \quad (Bo^* < 0.02) \quad (5a)$$

Transition region:

$$Nu = 49.0 Bo^{*0.41} We_e^{0.026} We_e^{0.17} \quad (0.02 < Bo^* < 0.024) \quad (5b)$$

Nucleate boiling region:

$$Nu = 731.96 Bo^{*0.85} We_e^{0.012} \quad (0.024 < Bo^*) \quad (5c)$$

As the heat transfer performance in both the single-phase and transition regions is strongly dependent on the applied ES potential, we have proposed the electric Weber number for Eqs. 5(a) and (b), which is defined as

$$We_e = \frac{\epsilon_f V_1^2}{\sigma D_i} \quad (6)$$

where ϵ_f is the electrical permittivity.

Fig. 10 compares the experimentally obtained Nu with that predicted using the proposed correlations. The mean absolute error (MAE) shows a significant improvement with respect to the predictions by taking the effect of electric field into consideration using Eq. (2).

Overall, the predicted values are fairly consistent with the experimental measurements, where the MAEs are 2.96% for the entire region, 5.87% for the single-phase region, 2.34% for the transition region, and 2.16% for the nucleate boiling region including the transition region.

4. Conclusions

We investigated the heat transfer performance of ES cooling using water as a working fluid. Three different flow rates, $Q = 200, 400$, and $600 \mu\text{L}/\text{min}$, were tested with the single stainless-steel nozzle with an inner diameter $D_i = 410 \mu\text{m}$. The effect of the applied ES potential (0–7 kV) on the ES modes was examined in detail. The important results of this study are summarized as follows:

- (1) The heat transfer behavior in the absence of an applied ES potential is quite similar for different flow rates. This is because the flow rate is very small, and the size of an impacting droplet is mainly determined by the gravitational force and surface tension.
- (2) The critical heat flux increases with the increase in the flow rate owing to the enhancements in the sensible and latent heats, resulting in a corresponding delay in dryout.
- (3) The applied ES potential enhances the heat transfer performance by $\sim 12.58\%$ and 6.65% in the single-phase and transition regions, respectively, owing to the generation of fine droplets, which frequently collide on the liquid film. However, no significant improvement is observed in the nucleate boiling region and at critical heat flux.
- (4) The variations in the ES mode are examined at different applied potentials and flow rates using sequential optical images captured by a high-speed camera.
- (5) New correlations are proposed for prediction of heat transfer for electrospray cooling. These correlations exhibit a good predictive capability over the entire range of applied ES potentials, with MAEs of 2.96% for all regions, 5.87% for the single-phase region, 2.34% for the transition region, and 2.16% for the nucleate boiling region including the transition region.

Declaration of Competing Interest

None.

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References

- [1] J. Lee, I. Mudawar, Two-phase flow in high-heat-flux micro-channel heat sink for refrigeration cooling applications: part II—heat transfer characteristics, *Int. J. Heat Mass Transf.* 48 (2005) 941–955, <https://doi.org/10.1016/j.ijheatmasstransfer.2004.09.019>.
- [2] K. Jambunathan, E. Lai, M.A. Moss, B.L. Button, A review of heat transfer data for single circular jet impingement, *Int. J. Heat Fluid Flow* 13 (1992) 106–115, [https://doi.org/10.1016/0142-727X\(92\)90017-4](https://doi.org/10.1016/0142-727X(92)90017-4).
- [3] H. Lee, T. Maitra, J. Palko, D. Kong, C. Zhang, M.T. Barako, Y. Won, M. Asheghi, K.E. Goodson, Enhanced heat transfer using microporous copper inverse opals, *J. Electron. Packag.* 140 (2018), <https://doi.org/10.1115/1.4040088>.
- [4] A.A. Hussien, M.Z. Abdullah, M.A. Al-Nimr, Single-phase heat transfer enhancement in micro/minichannels using nanofluids: theory and applications, *Appl. Energy* 164 (2016) 733–755, <https://doi.org/10.1016/j.apenergy.2015.11.099>.
- [5] W. Wu, G. Zhang, X. Ke, X. Yang, Z. Wang, C. Liu, Preparation and thermal conductivity enhancement of composite phase change materials for electronic thermal management, *Energy Convers. Manag.* 101 (2015) 278–284, <https://doi.org/10.1016/j.enconman.2015.05.050>.
- [6] D. Zhao, G. Tan, A review of thermoelectric cooling: materials, modeling and applications, *Appl. Therm. Eng.* 66 (2014) 15–24, <https://doi.org/10.1016/j.applthermaleng.2014.01.074>.
- [7] K.W. Jung, C.R. Kharangate, H. Lee, J. Palko, F. Zhou, M. Asheghi, E.M. Dede, K.E. Goodson, Embedded cooling with 3D manifold for vehicle power electronics application: single-phase thermal-fluid performance, *Int. J. Heat Mass Transf.* 130 (2019) 1108–1119, <https://doi.org/10.1016/j.ijheatmasstransfer.2018.10.108>.
- [8] J.W. Palko, H. Lee, C. Zhang, T.J. Dusseault, T. Maitra, Y. Won, D.D. Agonafer, J. Moss, F. Houshmand, G. Rong, J.D. Wilbur, D. Rockosi, I. Mykyta, D. Resler, D. Altman, M. Asheghi, J.G. Santiago, K.E. Goodson, Extreme two-phase cooling from laser-etched diamond and conformal, template-fabricated microporous copper, *Adv. Funct. Mater.* 27 (2017) 1703265, <https://doi.org/10.1002/adfm.201703265>.
- [9] J. Kim, Spray cooling heat transfer: the state of the art, *Int. J. Heat Fluid Flow* 28 (2007) 753–767, <https://doi.org/10.1016/j.ijheatfluidflow.2006.09.003>.
- [10] G. Liang, I. Mudawar, Review of spray cooling – part 1: single-phase and nucleate boiling regimes, and critical heat flux, *Int. J. Heat Mass Transf.* 115 (2017) 1174–1205, <https://doi.org/10.1016/j.ijheatmasstransfer.2017.06.029>.
- [11] D. Michelson, *Electrostatic Atomization*, Taylor & Francis, 1990.
- [12] S.J. Gaskell, Electrostatic spray: principles and practice, *J. Mass Spectrom.* 32 (1997) 677–688, [https://doi.org/10.1002/\(SICI\)1096-9888\(199707\)32:7<677::AID-JMS536>3.0.CO;2-G](https://doi.org/10.1002/(SICI)1096-9888(199707)32:7<677::AID-JMS536>3.0.CO;2-G).
- [13] A. Jaworek, Electrostatic micro- and nanoencapsulation and electroemulsification: a brief review, *J. Microencapsul.* 25 (2008) 443–468, <https://doi.org/10.1080/02652040802049109>.
- [14] A. Jaworek, Electrostatic droplet sources for thin film deposition, *J. Mater. Sci.* 42 (2007) 266–297, <https://doi.org/10.1007/s10853-006-0842-9>.
- [15] R.E. Hetrick, M.H. Parsons, Electrostatic spray for Fuel Injection, SAE International, Warrendale, PA, 1997, <https://doi.org/10.4271/972987>.
- [16] J.-H. Kim, H.-S. Lee, H.-H. Kim, A. Ogata, Electrostatic spray with electrostatic precipitator enhances fine particles collection efficiency, *J. Electrostat.* 68 (2010) 305–310, <https://doi.org/10.1016/j.elstat.2010.03.002>.
- [17] J.B. Fenn, M. Mann, C.K. Meng, S.F. Wong, C.M. Whitehouse, Electrostatic ionization for mass spectrometry of large biomolecules, *Science*. 246 (1989) 64–71, <https://doi.org/10.1126/science.2675315>.
- [18] X. Feng, J.E. Bryan, Application of electrohydrodynamic atomization to two-phase impingement heat transfer, *J. Heat Transf.* 130 (2008), <https://doi.org/10.1115/1.2885178>.
- [19] W. Deng, A. Gomez, Electrostatic cooling for microelectronics, *Int. J. Heat Mass Transf.* 54 (2011) 2270–2275, <https://doi.org/10.1016/j.ijheatmasstransfer.2011.02.038>.
- [20] H.-C. Wang, A.V. Mamashev, Heat transfer correlation models for electrostatic evaporative cooling chambers of different geometry types, *Appl. Therm. Eng.* 40 (2012) 91–101, <https://doi.org/10.1016/j.applthermaleng.2012.01.061>.
- [21] M.J. Gibbons, A.J. Robinson, Heat transfer characteristics of single cone-jet electrosprays, *Int. J. Heat Mass Transf.* 113 (2017) 70–83, <https://doi.org/10.1016/j.ijheatmasstransfer.2017.04.119>.
- [22] M.J. Gibbons, A.J. Robinson, Electrostatic array heat transfer, *Int. J. Therm. Sci.* 129 (2018) 451–461, <https://doi.org/10.1016/j.ijthermalsci.2018.03.021>.
- [23] J.D. Chapman, P.A. Kottke, A.G. Fedorov, Enhanced thin film evaporation via impinging electrospray liquid jets with entrained air streaming, *Int. J. Heat Mass Transf.* 131 (2019) 85–95, <https://doi.org/10.1016/j.ijheatmasstransfer.2018.11.049>.
- [24] G.I. Taylor, Disintegration of water drops in an electric field, *Proceed. Royal Soc. Lond. Ser. A Math. Phys. Sci.* 280 (1964) 383–397, <https://doi.org/10.1098/rspa.1964.0151>.
- [25] O. Lastow, W. Balachandran, Novel low voltage EHD spray nozzle for atomization of water in the cone jet mode, *J. Electrostat.* 65 (2007) 490–499, <https://doi.org/10.1016/j.elstat.2006.11.004>.
- [26] I. Hayati, A. Bailey, Th.F. Tadros, Investigations into the mechanism of electrohydrodynamic spraying of liquids: II. Mechanism of stable jet formation and electrical forces acting on a liquid cone, *J. Colloid Interface Sci.* 117 (1987) 222–230, [https://doi.org/10.1016/0021-9797\(87\)90186-X](https://doi.org/10.1016/0021-9797(87)90186-X).
- [27] B.K. Ku, S.S. Kim, Electrostatic characteristics of highly viscous liquids, *J. Aerosol Sci.* 33 (2002) 1361–1378, [https://doi.org/10.1016/S0021-8502\(02\)00075-7](https://doi.org/10.1016/S0021-8502(02)00075-7).
- [28] D. Parmentier, A. Rybicki, J. van Smeden, M.C. Kroon, J.C.M. Marijnissen, L. Lemos, Applying electrohydrodynamic atomization to enhance mass transfer of metal salts from an aqueous phase towards ionic liquids, *J. Electrostat.* 80 (2016) 1–7, <https://doi.org/10.1016/j.elstat.2015.11.007>.
- [29] M.L. Sweet, D. Pestov, G.C. Tepper, J.T. McLeskey, Electrostatic aerosol deposition of water soluble polymer thin films, *Appl. Surf. Sci.* 289 (2014) 150–154, <https://doi.org/10.1016/j.apsusc.2013.10.124>.
- [30] L.L.F. Agostinho, B. Bos, A. Kamau, S.P. Brouwer, E.C. Fuchs, J.C.M. Marijnissen, Simple-jet mode electrosprays with water. Description, characterization and application in a single effect evaporation chamber, *J. Aerosol Sci.* 125 (2018) 237–250, <https://doi.org/10.1016/j.jaerosci.2018.04.010>.
- [31] U. Stachewicz, C.U. Yurteri, J. Frits Dijkman, J.C.M. Marijnissen, Single event electrospraying of water, *J. Aerosol Sci.* 41 (2010) 963–973, <https://doi.org/10.1016/j.jaerosci.2010.06.004>.
- [32] J.-P. Borra, Review on water electro-sprays and applications of charged drops with focus on the corona-assisted cone-jet mode for high efficiency air filtration by wet electro-scrubbing of aerosols, *J. Aerosol Sci.* 125 (2018) 208–236, <https://doi.org/10.1016/j.jaerosci.2018.04.005>.
- [33] M.C. Shaw, J.R. Waldrop, S. Chandrasekaran, B. Kagalwala, X. Jing, E.R. Brown, V.J. Dhir, M. Fabbeo, Enhanced thermal management by direct water spray of high-voltage, high power devices in a three-phase, 18-hp AC motor drive demonstration, *ITherm 2002. Eighth Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (Cat. No.02CH37258)*, 2002, pp. 1007–1014, <https://doi.org/10.1109/ITHERM.2002.1012567>.
- [34] A.R. Jones, K.C. Thong, The production of charged monodisperse fuel droplets by electrical dispersion, *J. Phys. D. Appl. Phys.* 4 (1971) 1159–1166, <https://doi.org/10.1088/0022-3727/4/8/316>.
- [35] H.R. Shanks, P.D. Maycock, P.H. Sidles, G.C. Danielson, Thermal conductivity of silicon from 300 to 1400°K, *Phys. Rev.* 130 (1963) 1743–1748.
- [36] D.P.H. Smith, The electrohydrodynamic atomization of liquids, *IEEE Trans. Ind. Appl.* IA-22 (1986) 527–535, <https://doi.org/10.1109/TIA.1986.4504754>.
- [37] J. Zeleny, Instability of electrified liquid surfaces, *Phys. Rev.* 10 (1917) 1–6, <https://doi.org/10.1103/PhysRev.10.1>.
- [38] M. Cloupeau, B. Prunet-Foch, Electrohydrodynamic spraying functioning modes: a critical review, *J. Aerosol Sci.* 25 (1994) 1021–1036, [https://doi.org/10.1016/0021-8502\(94\)90199-6](https://doi.org/10.1016/0021-8502(94)90199-6).
- [39] R.P.A. Hartman, D.J. Brunner, D.M.A. Camelot, J.C.M. Marijnissen, B. Scarlett, Electrohydrodynamic atomization in the cone-jet mode physical modeling of the liquid cone and jet, *J. Aerosol Sci.* 30 (1999) 823–849, [https://doi.org/10.1016/S0021-8502\(99\)00033-6](https://doi.org/10.1016/S0021-8502(99)00033-6).
- [40] J.-P. Borra, P. Ehouarn, D. Boulaud, Electrohydrodynamic atomization of water stabilised by glow discharge—operating range and droplet properties, *J. Aerosol Sci.* 35 (2004) 1313–1332, <https://doi.org/10.1016/j.jaerosci.2004.05.011>.
- [41] I. Park, W.S. Hong, S.B. Kim, S.S. Kim, Experimental investigations on characteristics of stable water electrospray in air without discharge, *Phys. Rev. E* 95 (2017) 063110, <https://doi.org/10.1103/PhysRevE.95.063110>.
- [42] J.R. Rybicki, I. Mudawar, Single-phase and two-phase cooling characteristics of upward-facing and downward-facing sprays, *Int. J. Heat Mass Transf.* 49 (2006) 5–16, <https://doi.org/10.1016/j.ijheatmasstransfer.2005.07.040>.