Contents lists available at ScienceDirect



International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Electrospray cooling for microelectronics

Weiwei Deng^a, Alessandro Gomez^{b,*}

^a Department of Mechanical, Material and Aerospace Engineering, University of Central Florida, 4000 Central Florida Blvd, Orlando, FL 32816, USA ^b Department of Mechanical Engineering and Material Science, Yale University, 9 Hillhouse Ave., New Haven, CT 06520, USA

ARTICLE INFO

Article history: Received 6 July 2010 Received in revised form 2 August 2010

Keywords: Spray cooling MEMS Electrospray

ABSTRACT

The challenge of effectively removing high heat flux from microelectronic chips may hinder future advancements in the semiconductor industry. Spray cooling is a promising solution to dissipate high heat flux, but traditional sprays suffer from low cooling efficiency partly because of droplet rebound. Here we show that electrosprays provide highly efficient cooling by completely avoiding the droplet rebound, when the electrically charged droplets are pinned on the heated conducting surface by the electric image force. We demonstrate a cooling system consisting of microfabricated multiplexed electrosprays in the cone-jet mode generating electrically charged microdroplets that remove a heat flux of 96 W/cm² with a cooling efficiency reaching 97%. Scale-up considerations suggest that the electrospray approach is well suited for practical applications by increasing the level of multiplexing and by preserving the system compactness using microfabrication.

© 2011 Elsevier Ltd. All rights reserved.

IEAT and M

1. Introduction

Advancements of integrated circuits (IC) have recently been hampered by the severe challenge of the removal of high heat flux. Effective chip cooling may become the bottleneck of further progress in the microelectronic industry. Compared to conventional fan cooling that often relies on a thermal spreader, cooling by direct liquid impingement on the chip back side is promising for high heat flux removal, because it eliminates contact thermal resistance, promotes high velocity gradients that favor heat dissipation, and exploits the liquid latent heat when phase change occurs [1]. The coolant can take the form of impinging jets [1–3] or sprays [4,5]. Microjet arrays generated by silicon microfabricated nozzles with open [2] or closed drainage [3,4] are examples of jet cooling. Spray cooling, currently used in some supercomputers such as the CRAY X1. in principle is more effective than jet impingement cooling [6], mainly because the liquid film formed by sprays is typically much thinner (by a factor of 10) than that of liquid jets [7].

The physical process of spray cooling results from the impact of droplets on a heated surface, which, in turn, may lead to splash, spread, or rebound [8]. Especially when the surface temperature is higher than the Leidenfrost point of the liquid, the droplet tends to rebound because the pressure of the vapor below the liquid partially lifts the droplet [9]. As a result, in conventional sprays only a fraction of the liquid cooling capacity is exploited because of this rebound loss.

A possible approach to reduce or even entirely eliminate this loss is to electrically charge the droplets with respect to the hot conducting surface and rely on Coulombic attraction, if charge leakage on contact is sufficiently slow [10]. In this context, the electrospray (ES) is potentially well-suited for cooling purposes because of its unique properties. Although there are numerous functioning modes of this device [11,12], the most appealing one from the point of view of achieving fine liquid dispersion with ensuing enhanced evaporation in a relatively short time is the so-called cone-jet mode [13]. In that mode an electrohydrodynamic process is established in which a spray of monodisperse droplets is formed by passing a liquid with sufficient electrical conductivity through a capillary charged to a high potential with respect to a ground electrode a short distance away. Under the effect of a high electric field, the liquid meniscus takes the shape of a cone from the tip of which a thin liquid thread emerges, leading to the cone-iet mode [13]. This microiet breaks into a stream of charged droplets that eventually spread to form a spray. Among the key features distinguishing the electrospray from other atomization techniques are: the quasi-monodispersity of the droplets; the Coulombic repulsion of the charged droplets, which induces spray selfdispersion, prevents droplet coalescence and enhances mixing; and the capability of producing droplets of uniform size even at the nanoscale. In addition, the number density is reasonably uniform throughout the spray. The inner diameter of the ES nozzle is typically $10-100 \times$ larger than the droplet, which reduces the risk of clogging and dramatically decreases the liquid pressure drop, from $\sim 10^5$ Pa of a conventional atomizer [14] to $\sim 10^3$ Pa of ES systems.

ES has been widely used in ionization mass spectroscopy [15]. In virtually all other applications, it has been plagued by one

^{*} Corresponding author. Tel.: +1 203 432 4384; fax: +1 203 432 7654. *E-mail address*: Alessandro.Gomez@yale.edu (A. Gomez).

^{0017-9310/\$ -} see front matter \odot 2011 Elsevier Ltd. All rights reserved. doi:10.1016/j.ijheatmasstransfer.2011.02.038

critical drawback: the low flow rate of a single ES source, which would make it inadequate even for spray cooling. This drawback has been recently overcome by microfabricated multiplexed ES (MES) systems [16,17], which allow for the dispersion of large total flow rates through multiple, densely packed ES sources operating in parallel. Applications of MES in combustion [18], material synthesis [19] and electric propulsion [20] have recently been reported. In the context of spray cooling, the "digital" version [21] of the MES devices, in which each individual spray can be turned on/off selectively via electronic control, has also the potential for local thermal management of hot spots on microelectronic chips.

ES cooling has been attempted in [22] but the authors operated a single ES in a broad range of flow rates and voltage with relatively coarse dispersion of the liquid, that is outside the desirable conejet mode. In fact, optimal behavior is reported in the "ramified" regime, that, on physical ground should be far less promising than the fine atomization of the cone-jet mode. A $4\times$ modest level of multiplexing by conventional fabrication was reported in the non-peer reviewed literature with a promising cooling enhancement [23], but few details are available in the abstract to assess those claims. Here we report on an application to microelectronic chip cooling of a compact, microfabricated MES device operating in the cone-jet mode. We will demonstrate a miniaturized MES cooling device that removes a heat flux of 96 W/cm², with the potential of additional scale up, and with an unprecedented cooling efficiency reaching up to 97%.

2. Experimental setup

MES fabrication and testing details are documented elsewhere [16,17]. Here we summarize briefly its main features. The device has a 3-layer structure (Fig. 1a): a liquid distributor layer microfabricated in silicon with multiple nozzles (Fig. 1b) as ES sources held at high voltage V_1 , an extractor electrode layer held at an intermediate voltage V_2 , and a glass insulator/spacer layer sandwiched

between the distributor and the extractor. The value $(V_1 - V_2)$ is fixed at 1.5 kV, while V_2 is varied from 1 to 3 kV. Fig. 1c and d provides a glimpse of the progress made in multiplexing and compacting these devices, with the visualization of sprays generated by two MES devices: a 91-nozzle chip with packing density of 253 sources/cm², and a 19-nozzle chip with a packing density of 11,000 sources/cm². In the present work, we use 19 or 37 nozzles with a packing density of 253 sources/cm² and with a footprint of 7.6 mm² and 14.8 mm², respectively. The sprays diverge with a semi-angle of ~10° and can cover the entire 16 mm² of the thermal test element.

A liquid coolant such as ethanol with a boiling point of 78.3 °C is supplied at flow rates ranging between 25 cc/h and 100 cc/h through the entire MES device to deliver charged droplets with typical mean diameter (d_{10}) of 25 µm and a relative standard deviation (RSD) of 10%, as measured by Phase Doppler Anemometry (PDA). All diameter values used in this work refer to d_{10} . The accuracy of the PDA is also confirmed by the video frames recorded using a high speed camera, as will be explained shortly. The flow rate is set by a syringe pump with an uncertainty $\pm 1\%$. The droplet size is fine-tuned by adjusting K, the electrical conductivity of the liquid, for example by doping the liquid with PPM level of 1-ethyl-3-methylimidazolium ethylsulfate, an ionic liquid (IL). To measure K, we first measured the resistance $R_{\rm L}$ of a liquid column confined in a Teflon tubing with known cross section area $A_{\rm L}$ and length L, and then used the equation $K = L/R_LA_L$. Additional physical properties of ethanol are listed in Table 1.

Fig. 2 depicts the setup for the heat transfer experiments, with the components in Fig. 1a and b, clearly identified. We use four Resistance Temperature Detector (RTD) elements (Omega, Model F2020, Class B) as both temperature sensor and heater to mimic the Joule heating of a microelectronic chip. Each RTD measures $2 \times 2 \times 0.38 \text{ mm}^3$, has a thin, narrow, and meandering platinum resistance path sandwiched between the glass coating and the 380 µm-thick Alumina ceramic base with a high thermal conduc-



Fig. 1. MES device. (a) A device schematic showing the key components including liquid reservoir, silicon nozzle chip, and the extractor. (b) Scanning electron micrographs (SEM) of a 19-nozzle array. (c) Spray visualization of a 91-nozzle MES system with packing density of 253 sources/cm². (d) Spray visualization of a 19-nozzle system with packing density of 11,000 sources/cm².

Table 1

Physical properties of the ethanol (200 Proof, Pharmco) used in this work.				
Properties	Boiling point	Electrical conductivity	Mass density	Heat of evaporation
Symbols Units Value	<i>T_b</i> °C 78 3	K S/m 1.3 × 10 ⁻⁵	hokg/m ³ 781	h _{evp} kJ/kg 854

tivity of 20 W/(m K). The RTDs provide accurate temperature sensing with an uncertainty better than ±0.8 °C. We record the voltage V_0 and current I_0 to compute the heating power $P_0 = V_0 I_0$ and the resistance $R_0 = V_0/I_0$. The heater temperature T can be calculated using the Callendar–Van Dusen equation $R_0 = 100(1 + B \cdot T + C \cdot T^2)$, where $B = 3.9083 \times 10^{-3}$ /°C and $C = -5.775 \times 10^{-7}$ /(°C)². The heat flux is determined using P_0/A , where A is the heater area. The uncertainty of the heat flux is estimated at ±2%. The temperature scan is realized by manually and slowly ramping up the voltage of the DC power supply. The top surface of the RTDs is coated with a thin layer of graphite and then connected to the ground of the high voltage power supply. The surface temperature of the RTD is evaluated using the heat flux, the ceramic chip thickness, and the ceramic thermal conductivity. The typical temperature drop from the Pt film to the RTD surface is ~ 10 K. The uncertainty of the surface temperature is ±3 K. The bottom of the RTDs is thermally insulated. The distance between the extractor and the thermal test chip is nearly 5 mm. An air co-flow at 2 L/min is passed through the extractor to sweep away any liquid accumulation caused by vapor condensation on the extractor. The air flow may also provide up to 3.5 W cooling capacity, or 22% of the highest heat flux we tested. The overall electrospray cooler assembly is very compact $(12.5 \times 12.5 \times 5 \text{ mm})$ thanks to the compactness of the MES chip. The experiments are conducted in an unconfined environment and the liquid is not recirculated.

Details of the droplet impact process are obtained by using a high-speed camera (Phantom V7.3) and a $10 \times$ microscope objective lens connected with a bellow attachment. The light source is a high power blue light emitting diode (LED) coupled

with a condenser. The use of single color LED avoids heating to the droplets. The working distance of the lens is 12 mm, which allows us to image the entire cross section of the spray. We adjust the bellows extension to achieve an optical magnification rate of $25\times$, and the numerical aperture is 0.04, resulting in a depth of field (DOF) of ~100 μ m. Because the electrospray is dilute, the DOF is short compared to the average inter-droplet distance near the heater surface; therefore we can optically distinguish an individual droplet from its neighbors. The video frames are analyzed using the software Image] (NIH) [24].

3. Results and discussion

3.1. Droplet impact on heated surface

The droplet impact dynamics is usually classified in terms of Weber number $We = \rho d v_0^2 / \gamma$ and Ohnesorge number $Oh = \mu / \rho$ $(\rho\gamma d)^{1/2}$, where ρ is the liquid mass density, v_0 is the droplet impacting velocity, *d* is the droplet diameter before impact, γ is the liquid interfacial tension, and μ is the liquid dynamic viscosity, respectively [25]. We is the ratio between the inertial and the surface tension forces, while Oh relates the viscous force to inertial and surface tension forces. For typical ES droplets impacting a grounded surface, $We \sim O(10)$ and $Oh \sim O(0.1)$, corresponding to a relatively gentle impact with droplet spreading, but without splashing. The critical parameter that has a significant effect is the surface temperature T_s . When T_s is sufficiently larger than the fluid boiling point, a thin vapor layer forms between the bottom of the droplet and the substrate upon impact. This condition corresponds to the well-known Leidenfrost point [26]. At this point, the contact angle is nearly 180°, and a microdroplet generally tends to experience rebound.

Once the droplets are electrically charged, if the impact time [27] $\tau_{im} = 8d/3v_0 = 8 \ \mu s$ is less than the charge relaxation time $\tau_r = \varepsilon/K = 16 \ \mu s$, where *d* is the droplet diameter, and ε is the dielectric permittivity of the liquid, the charge leakage from the droplet to the substrate is relatively slow. Since the droplet remains sufficiently charged even after impact, it experiences an additional



Fig. 2. Experimental setup for MES cooling.

Coulombic attraction force (image force) with the substrate [10]. For picoliter droplets, the image force is three orders of magnitude larger than gravity and may help prevent rebound. The high-speed image sequence shown in Fig. 3a confirms that the image force binds the droplet on the surface and hinders rebound. For the same surface temperature, on the other hand, we found that both electrically neutral picoliter droplet and the charged large droplets (~0.1 nL) do experience rebound, as shown in Fig. 3b and c. In the case in Fig. 3c, t_{im} is much longer (~70 µs) and the charge transport from the droplet to the conducting surface is completed during contact. As a result, the image force plays no role in the post-impact developments.

It is also worth mentioning that even at substrate temperatures much lower than the Leidenfrost point [28] when the droplet does not rebound, charged droplets exhibit smaller apparent contact angles as compared to neutral droplets because of the image force [10]. Consequently, the charged droplets have larger surface-tovolume ratios and higher evaporation rates, which, in turn, translate into a higher heat flux extraction capability.

3.2. Typical cooling behavior

Fig. 4 shows a typical cooling curve, i.e., removed heat flux vs. surface temperature T_s , for a MES cooling system operated at a total flow rate of 100 cc/h. The graph contains two regions. The first $(T_{\rm s} < 55 \,^{\circ}{\rm C})$ exhibits an approximately linear behavior with a slope smaller than the second region ($T_s > 55 \text{ °C}$), suggesting that the heat transfer mechanism is primarily single-phase convection, and the heat flux is too low to heat up the excess liquid to the boiling point (T_b) . At the beginning of the second region $(T_s > 55 \text{ °C})$, the phase change becomes apparent, as evidenced by a steeper slope that is about twice that of the first region. As the superheat $(T_s - T_b)$ increases, the slope of the curve gradually decreases. At 100 °C, the curve reaches the upper limit of heat flux removed, i.e., the critical heat flux (CHF), of 96 W/cm², when cooling cannot keep up with heating. The general behavior of Fig. 4 is consistent with typical spray cooling [29] except for the fact that the twophase region starts \sim 20 K below T_b in Fig. 4, while ordinarily the two-phase region starts 3-5 K above T_b . The difference is because the size of the electrosprayed droplet is much smaller than the droplets typically generated by conventional atomizers. The small droplet diameter results in significantly shortened evaporation



Fig. 3. High-speed photograph of droplet impacts showing (a) no rebound for a electrically charged picoliter droplet; (b) immediate rebound for an electrically neutral picoliter droplet; and (c) immediate rebound for a nanoliter droplet. Substrate temperature is 120 °C; camera speed and shutter time are 125,000 frames/s and 1 μ s, respectively; droplet diameter and impact velocity are reported in the first column.



Fig. 4. Typical MES cooling curves with ethanol at a total flow rate of 100 cc/h.

times that may be comparable to the droplet travel time before contacting the substrate. An estimate of the droplet evaporation time for a typical droplet diameter of 25 microns computed with a modified film model [30] yielded a value of \sim 2 ms with a gas temperature at 55 °C, which is of the same order as the droplet residence time, suggesting that the droplet experiences noticeable evaporation even before the boiling point is reached.

A parameter used to evaluate the cooling performance is the cooling efficiency [29], that is defined as the ratio of removed heat flux to the theoretical upper limit of the cooling capacity, i.e.,

$$\eta_e = \frac{q}{\dot{m}_l c(T_b - T_0) + \dot{m}_l h_{evp} + \dot{m}_{air} c_{p,air}(T_s - T_0) + \dot{m}_l c_{p,v}(T_s - T_b)}$$
(1)

where η_e is the cooling efficiency, \dot{q} is the heat flux removed by the cooling device. The latter is accurately quantified by measuring the heating power $P_0 = V_0 I_0$ at steady state and heater area A, as described in Section 2. The denominator of Eq. (1) is the theoretical upper limit of the cooling capacity, i.e., the sum of the heat flux needed to raise the liquid temperature to boiling point, the liquid latent heat, and the enthalpy rise of the gas and vapor, where m_1 is the total liquid mass flow rate, c is the liquid specific heat, T_b is the boiling point, T_0 is the initial temperature of the spray and gaseous co-flow, h_{evp} is the fluid latent heat per unit mass, \dot{m}_g is the gas mass flow rate, $c_{p,air}$ is the gas specific heat at constant pressure, and $c_{p,v}$ is the coolant vapor specific heat at constant pressure. MES cooling appears to be guite efficient. At the CHF in Fig. 4, the system reaches a cooling efficiency of 60%, a value that could be further improved by using smaller droplet sizes, as discussed in the next section.

3.3. Effect of droplet diameter

At a constant total flow rate, the droplet diameter can be finetuned either by changing the liquid conductivity *K* with trace amount of ionic liquid additives or by partitioning the total flow rate through more electrospray sources, that is by increasing the multiplexing level. Here we implement the easier, first approach. Fig. 5 shows the relationship between droplet size and flow rate per nozzle for two liquids with different conductivities: pure ethanol with conductivity *K* measured at 1.3×10^{-5} S/m and ethanol doped with 1.6 PPM (by weight) of the ionic liquid, with conductivity *K* = 3.3×10^{-5} S/m. For the same flow rate per nozzle, a higher



Fig. 5. Droplet size scaling law for liquids with different conductivities.

conductivity decreases the droplet size and volume by about 20% and 60%, respectively.

Fig. 6 shows the cooling curves for two multiplexed electrosprays with different droplet sizes that operated at an identical total flow rate of 25 cc/h. The droplet size effect is twofold. First, the CHF is higher for smaller droplets. At Q = 25 cc/h, the MES with smaller droplets reaches a CHF 24% larger than that with larger droplets. Second, at the identical heat flux, the substrate cooled by smaller droplets has lower wall temperatures. For example, with Q = 25 cc/h and a heat flux of 40 W/cm^2 , the wall temperature is \sim 20 K cooler with smaller droplets. This suggests that smaller droplets lead to more effective cooling. Indeed, the efficiency was increased from 82% to 97% at CHF by decreasing droplet size for the same total flow rate of 25 cc/h. This result can be explained by the classic *D*-square law, stating that the droplet evaporation time scales with the square of droplet diameter D. Therefore, with a fixed total flow rate, smaller droplets evaporate faster in flight and during the contact with the hot surface. The faster evaporation rate results in a higher CHF and a higher cooling efficiency.



Fig. 6. Cooling curves for different droplet sizes at a total flow rate of 25 cc/h.

3.4. *Effect of flow rates*

Fig. 7 shows four cooling curves for multiplexed electrosprays operated with pure ethanol at 25, 50, 75 and 100 cc/h. All curves show the double-slope behavior as for the cooling curve in Fig. 4. As the total flow rate increases from 25 to 100 cc/h, the CHF more than doubles from 40 W/cm² to 96 W/cm². This finding is not surprising because a higher coolant flux is capable of removing more heat flux. At the same time, the temperature at which CHF is reached also increases with the liquid flow rate, because as the latter increases, more superheat is needed to evaporate a given amount of liquid.

One disadvantage of higher flow rates is the decline in cooling efficiency from 82% at 25 cc/h to 60% at 100 cc/h. The droplet size scaling law shown in Fig. 5 may explain this phenomenon. Fig. 5 clearly shows the droplet size has a monotonic dependence on the liquid flow rate, i.e., $d \propto Q^{\alpha}$, where *d* is the droplet diameter, and α is the exponent of the power law that is approximately 0.5 for ethanol. The scaling law suggests that increasing the total flow rate from 25 cc/h to 100 cc/h will approximately double the droplet size. Larger droplets have longer contact time upon impact, thus more electric charge will be transferred to the substrate. As a result, less image force is applied and the droplet is more likely to rebound. The rebound droplets contribute to a loss of cooling capacity, and eventually results in a decreased cooling efficiency.

High heat flux removal and high cooling efficiency can be achieved simultaneously if we maintain both large flow rates and small droplets, which can be realized by increasing the total number of nozzles and thus reducing the average flow rate delivered by each nozzle. Considering the restriction of the area of a given microelectronic chip, the packing density of the ES sources needs to be increased so as to integrate more nozzles per unit area, as demonstrated in [17].

3.5. Practical considerations

In general two-phase cooling is more challenging to implement than single-phase cooling, because of the added complexity of liquid pumping, sealing, recirculation, and vapor condensation. Cost, efficiency, and CHF requirements for specific applications define trade-off considerations for the thermal engineer.

Specific to electrospray cooling is the additional requirement of high voltage to establish the cone-jet mode. However, the electric



Fig. 7. MES cooling performance for different total flow rates from 25 cc/h and 100 cc/h.

power needed to generate the electrospray is very modest. The typical voltage used in this work is 1.5 kV, and the current draw per electrospray is only ~10 nA. Therefore, the consumed power per nozzle is ~1 mW, which is negligible compared to the dissipated thermal power per spray of at least 1 W and, in turn, to the power requirement of the integrated circuit. Miniaturized low current/high voltage power supplies are commercially available or can be easily constructed using the Cockcroft Walton multiplier.

Furthermore, the minor complication associated with the high voltage supply can be partly offset by a reduction in pumping power: the low pressure drop of ~5000 Pa across each nozzle, combined with a typical coolant flow rate per nozzle of 1 cc/h of the examples considered in this article, results in a net pumping power of only ~10 μ W per nozzle, a decrease by two orders of magnitude as compared to conventional sprays (~1 mW). As a result parasitic losses associated with powering the electrospray cooling system are indeed very modest and would not be taxing in the overall balance of plant.

To generate the electrospray, the coolant should have finite electrical conductivity. Typical polar liquids such as deionized water and ethanol can meet this requirement. If the cooling system has components that are chemically incompatible with polar liquids, nonpolar ones, doped with suitable additives to enhance their otherwise very low electric conductivity, can also be used. For example, JP-8, a kerosene based jet fuel, showed good electrospray properties after doping with as little as 0.1% (weight) of Statis 450 (Dupont) [18].

4. Conclusion

In summary, we showed that electrically charged microdroplets can fully exploit the droplet cooling capacity by avoiding rebound from the surface as a result of the electric image force. We demonstrated a cooling system consisting of microfabricated multiplexed electrospray to generate electrically charged microdroplets that removed a heat flux of 96 W/cm² with a cooling efficiency reaching 97%. Further increases in cooling capabilities and efficiencies are possible with an increase in the number of electrospray sources per unit area, which is feasible with the spatial resolution of current microfabrication techniques. High cooling efficiency allows for the circulation of coolant at low flow rates, which directly contributes to a reduction in the overall system weight and energy use. The compactness and high efficiency of the MES device makes it potentially well suited for cooling of microelectronic chips in a broad range of applications.

Acknowledgement

We thank C. Mike Waits, Nicholas R. Jankowski, Brian Morgan and Bruce R. Geil for the microfabrication work. The support from the U.S. Army (W911NF-05-2-0015) is gratefully acknowledged.

References

 A. Bar-Cohen, M. Arik, M. Ohadi, Direct liquid cooling of high flux micro and nano electronic components, Proc. IEEE 94 (2006) 1549–1570.

- [2] C.H. Amon, J. Murthy, S.C. Yao, S. Narumanchi, C. Wu, C. Hsieh, MEMS-enabled thermal management of high-heat-flux devices EDIFICE: embedded droplet impingement for integrated cooling of electronics, Exp. Therm. Fluid Sci. 25 (2001) 231–242.
- [3] E.N. Wang, L. Zhang, L. Jiang, J. Koo, J.G. Maveety, E.A. Sanchez, K.E. Goodson, T.W. Kenny, Micromachined jets for liquid impingement cooling of VLSI chips, J. Microelectromech. Syst. 13 (2004) 833–842.
- [4] B. Agostini, J.R. Thome, M. Fabbri, B. Michel, D. Calmi, U. Kloter, High heat flux flow boiling in silicon multi-microchannels – Part I: heat transfer characteristics of refrigerant R236fa, Int. J. Heat Mass Transfer 51 (2008) 5400–5414.
- [5] J.R. Rybicki, I. Mudawar, Single-phase and two-phase cooling characteristics of upward-facing and downward-facing sprays, Int. J. Heat Mass Transfer 49 (2006) 5–16.
- [6] S. Freund, A.G. Pautsch, T.A. Shedd, S. Kabelac, Local heat transfer coefficients in spray cooling systems measured with temperature oscillation IR thermography, Int. J. Heat Mass Transfer 50 (2007) 1953–1962.
- [7] C. Sodtke, P. Stephan, Spray cooling on micro structured surfaces, Int. J. Heat Mass Transfer 50 (2007) 4089–4097.
- [8] M. Rein, Phenomena of liquid drop impact on solid and liquid surfaces, Fluid Dyn. Res. 12 (1993) 61–93.
- [9] S. Chandra, C.T. Avedisian, On the collision of a droplet with a solid surface, Proc. Roy. Soc. London. Ser. A 432 (1991) 13.
- [10] W. Deng, A. Gomez, The role of electric charge in microdroplets impacting on conducting surfaces, Phys. Fluids 22 (2010) 51703.
- [11] J. Zeleny, Instability of electrified liquid surfaces, Phys. Rev. 10 (1917) 1-6.
- [12] M. Cloupeau, B. Prunet-Foch, Electrostatic spraying of liquids: main functioning modes, J. Electrostat. 25 (2) (1990) 165-184.
- [13] M. Cloupeau, B. Prunet-Foch, Electrostatic spraying of liquids in cone-jet Mode, J. Electrostat. 22 (1989) 135–159.
- [14] C.H. Chen, E.M. Kelder, M.J.G. Jak, J. Schoonman, Electrostatic spray deposition of thin layers of cathode materials for lithium battery, Solid State Ionics 86–88 (1996) 1301–1306.
- [15] J.B. Fenn, M. Mann, C.K. Meng, S.F. Wong, C.M. Whitehouse, Electrospray ionization for mass spectrometry of large biomolecules, Science 246 (1989) 64–71.
- [16] W. Deng, J.F. Klemic, X. Li, M.A. Reed, A. Gomez, Increase of electrospray throughput using multiplexed microfabricated sources for the scalable generation of monodisperse droplets, J. Aerosol Sci. 37 (2006) 696–714.
- [17] W. Deng, C.M. Waits, B. Morgan, A. Gomez, Compact multiplexing of monodisperse electrosprays, J. Aerosol Sci. 40 (2009) 907–918.
- [18] W. Deng, J.F. Klemic, X. Li, M.A. Reed, A. Gomez, Liquid fuel combustor miniaturization via microfabrication, Proc. Combust. Inst. 31 (2006) 2239– 2246.
- [19] B. Almería, W. Deng, T. Fahmy, A. Gomez, Controlling the morphology of electrospray-generated PLGA microparticle for drug delivery, J. Colloid Interface Sci. 343 (2010) 125–133.
- [20] G. Lenguito, J. Fernandez de la Mora, A. Gomez, Multiplexed electrospray for space propulsion applications, in: AIAA Joint Propulsion Conference, vol. 46, AIAA-2010-6521, 2010.
- [21] W. Deng, C.M. Waits, A. Gomez, Digital electrospray for controlled deposition, Rev. Sci. Instrum. 81 (2010) 35114.
- [22] X. Feng, J.E. Bryan, Application of electrohydrodynamic atomization to twophase impingement heat transfer, J. Heat Transfer Trans. ASME 130 (2008) 072202.
- [23] H.C. Wang, C.P. Hsu, A.V. Mamishev, The enhancement ratio of corresponding convection heat transfer coefficient using electrospray evaporative cooling system, in: ASME 2009 Heat Transfer Summer Conference, San Francisco, California, USA, 2009.
- [24] Available from: <http://rsbweb.nih.gov/ij/>.
- [25] S. Schiaffino, A.A. Sonin, Molten droplet deposition and solidification at low Weber numbers, Phys. Fluids 9 (1997) 3172–3187.
- [26] J.D. Bernardin, C.J. Stebbins, I. Mudawar, Mapping of impact and heat transfer regimes of water drops impinging on a polished surface, Int. J. Heat Mass Transfer 40 (1997) 247–267.
- [27] M. Pasandideh-Fard, Y.M. Qiao, S. Chandra, J. Mostaghimi, Capillary effects during droplet impact on a solid surface, Phys. Fluids 8 (1996) 650–659.
- [28] A.B. Wang, C.H. Lin, C.C. Chen, The critical temperature of dry impact for tiny droplet impinging on a heated surface, Phys. Fluids 12 (2000) 1622.
- [29] J. Kim, Spray cooling heat transfer: the state of the art, Int. J. Heat Fluid Flow 28 (2007) 753–767.
- [30] B. Abramzon, W.A. Sirignano, Droplet vaporization model for spray combustion calculations, Int. J. Heat Mass Transfer 32 (1989) 1605–1618.