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Electrospray array heat transfer

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ABSTRACT

Multiple source electrospraying enables higher droplet mass flux and greater cooling coverage area in comparison with its single source counterpart. The local convective heat flux to a multiple source electrospray array has been experimentally investigated using thin foil thermography. The designed array had a packing density of 115 N_n and was operated in the cone-jet regime of spraying with ethanol as the working fluid. The electrospray array heat transfer performance is explored for varied flow rates (Q = 2–4 μL min^{-1} N_n^{-1}) and electric fields (E_d = 4–8 kV cm^{-1}). Cooling performance was shown to be dependent on both parameters. An 89% and 64% increase in the peak and average heat flux respectively was measured for the increasing electric field strength. This was due to increasing droplet mass flux, resulting in increasing contact line length density on the heated substrate, from narrowing of the spray plume, reduced residence time and droplet evaporation en-route to the target surface. This narrowing spray plume, at higher driving electric fields, also resulted in a more defined radial convective heat flux profile. The performance of the array was compared with that of a single source under similar experimental conditions. The array achieved more uniform cooling over a larger area than its single source counterpart. Comparing both devices for similar total working fluid flow rate highlight that the array delays the onset of pool cooling. This enables higher total working fluid flow rates in the evaporative cooling regime and subsequently higher convected thermal energy transport.

1. Introduction

There is a growing expectation on small form factor electronics to be more compact while also increasing performance. This trend has resulted in increasing generated heat flux density due to the increasing transistor density, chip resistance, capacitance, and subsequent charge leakage [1]. This progression has driven conventional cooling technologies to a thermal management threshold, where they are unable to remove the generated thermal load with the required thermal resistance. Future high speed processor are predicted to achieve heat fluxes of 500 W cm^{-2} ranging up to 1000 W cm^{-2}at hot spots [2–4]. Forced air convection can achieve a heat flux removal of 150 W cm^{-2} [5], while 120 W cm^{-2} can be obtained through pool boiling of water [6]. In order to maintain chip performance, life cycle and avoid component failure it is imperative to keep on-chip surface temperatures below 85°C [7–9]. Clearly a step change in thermal management technology is required to overcome the thermal load generated from the next generation of microelectronics. An emerging solution to this problem is cone-jet electrospray cooling (EC).

Electrospraying is a method of fluid atomisation by electrostatic means (see Fig. 1). It can be divided into a number of different operating regimes, some of which were initially identified by Zeleny [10,11] and later more comprehensively classified by Cloupeau and Prunet-Foch [12]. A widely applied functioning mode is the “cone-jet” regime characterised by Cloupeau and Prunet-Foch [13]. Cone-jet electrospray electrode design can be divided into two configurations: two electrode (source–target), and three electrode (source–extractor–target), and these are shown in Fig. 2. The three electrode design utilises an intermediate extractor electrode between the source and target electrodes. The extractor electrode typically consists of a thin plate (δ_{ex}~200 μm) with holes concentric to that of the source nozzles to allow the generated spray to pass through [14–16]. Both designs achieve cone-jet electrospraying in a similar manner but the three electrode configuration increases complexity and is normally applied in multiple source applications [15,17–20]. A comprehensive description of the electrospray cooling process has been discussed previously by Gibbons and Robinson [21]. An illustration of the three electrode electrospraying process and the relevant electrospray array length scales are shown in Fig. 3 and Fig. 4 respectively. In the three electrode configuration (Fig. 2b), a suitable working fluid is supplied to the tip of a source nozzle which is maintained at an electrical potential above that of an adjacent extractor electrode. This potential difference creates an electric field, and when a sufficient electric field is established, the meniscus at the tip of the source nozzle deforms into the shape of a liquid

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Nomenclature

C_p	specific heat capacity [J kg^{-1} K^{-1}]
D	nozzle diameter [μm]
H_1	source–extractor separation height [mm]
H_2	extractor–target separation height [mm]
I	current [A]
j_m	mass flux [kg m^{-2} s^{-1}]
k	thermal conductivity [W m^{-1} K^{-1}]
L	length [mm]
N_n	number of nozzles [−]
Q	working fluid flow rate [μL min^{-1}]
q	heat transfer rate [W]
q''	heat flux [W m^{-2}]
r	radial distance from nozzle centre [mm]
S	coordinate [mm]
s	nozzle spacing [mm]
T	temperature [K]
V	voltage [V]
W	energy [J]

Dimensionless Numbers

Bi	$Bi = hL/k$ [−]

Greek Symbols

δ	thickness [μm]
γ	surface tension [N m^{-1}]
ρ	density [kg m^{-3}]
σ	Stefan-Boltzmann constant [W m^{-2}K^{-4}]
ε	emissivity [−]

Subscripts

∞	bulk or infinity
ag	air gap
cap	capacitive or storage
ch	nozzle channel
cond	conduction
d	droplet
ex	extractor electrode
f	foil
gen	generated
i	inner
o	outer
j	jet
lc	lateral conduction
n	source nozzle
p	paint
rad	radiation
s	heated substrate
wf	working fluid
x, *y*, *z*	coordinate direction

Acronyms

CLD	contact line length density
DC	direct current
EC	electrospray cooling
IR	infrared
NC	natural convection
PEEK	polyether ether ketone
PU	percentage uncertainty

cone (see Fig. 1), often referred to as a Taylor cone [22]. This conical shape is as a result of the balance of surface tension, viscous, hydrostatic, gravitational, and electrostatic forces. At the apex of this cone a thin permanent jet is formed. The jet passing through the extractor electrode undergoes Rayleigh instability and breaks up into quasi-monodisperse micron-sized charged droplets. The generated droplets are then propelled towards the target ground electrode by the electric field between the extractor and target surface. Often two families of droplets are produced; primary and satellite. Primary droplets make up ≈ 97% of the flow and ≈ 86% of the current [23]. Coulombic repulsion of the charged droplets enables spray plume dispersion (Fig. 1) and droplet segregation, with primary droplets located in the core of the plume and satellite droplets orientated on the periphery of the spray due to their greater initial charge and reduced inertia in comparison

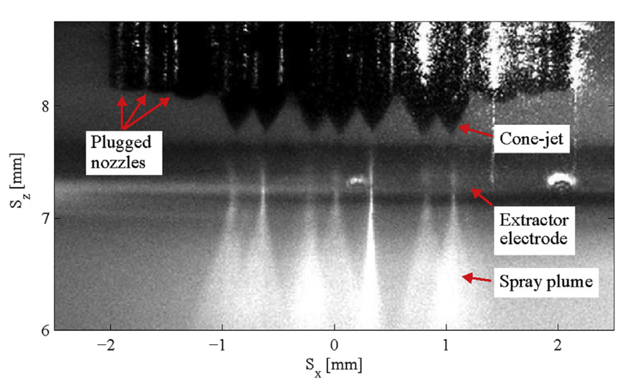

Fig. 1. Electrospray array. D_i = 200 μm, D_o = 400 μm, H_1 = 0.5 mm, H_2 = 7.5 mm, Q = 3 μL min^{-1} N_n^{-1}, V_n = 7.1 kV, V_{ex} = 6 kV, E_d = 8 kV cm^{-1}, and q''_{gen} = 1,395 W m^{-1}.

with primary droplets [23]. Coulomb attraction between the charged droplets and grounded target surface negates droplet rebound and increases droplet spreading during impact [24] resulting in a more effective heat transfer process [16,25].

The additional intermediate electrode enables localisation of the electric field at the source electrode and shields the cone-jet from the highly charged generated spray cloud [15]. The extractor design enables a more stable spray process and a degree of plume dispersion control [26]. Two separate electric fields exist in this design, the jet forming electric field (E_j) between the source and extractor and the driving electric field (E_d) between the extractor and target electrodes. Once a suitable potential drop is established between the source and extractor it is possible to vary the driving electric field to alter plume dynamics. Yang et al. [26] showed that a higher E_d resulted in a more concentrated plume. This is due to the increased droplet velocity in the spray direction arising from the increasing electric field. This results in a shorter droplet residence time allowing less time for plume dispersion. Deng and Gomez [27] defined a minimum E_d that is required to prevent "satellite trapping". This is flow reversal of satellite droplets back to the extractor electrode. This can result in flooding between the

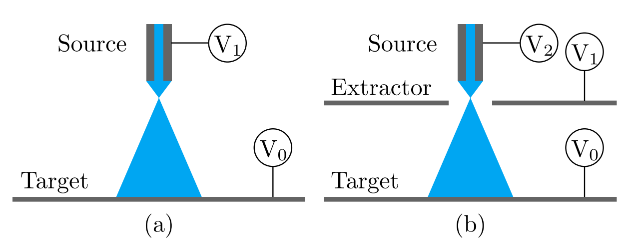

Fig. 2. Electrospray electrode configuration. (a) Two electrode design, (b) three electrode design.