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Experimental investigation of spray cooling on smooth and micro-structured surfaces

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ABSTRACT

The heat transfer during spray cooling was studied experimentally using deionized water to investigate the spray characteristics and the differences between spray cooling on smooth and enhanced silicon surfaces with micro-structures (characteristic size 25–200 μm). The spray cooling experiments show that the heat transfer was not significantly greater for the micro-structured surfaces than for the smooth surface in the flooded region, but was much greater in the thin film and partial dryout regions. The micro-structured surface with larger characteristic sizes had a smaller area enhancement factor and worse heat transfer rates. However, on the micro-structured surface with much smaller characteristic sizes, most droplets were not able to completely enter the bottom of the micro grooves since the groove size was smaller than most of the droplets and the heat transfer surface could not be fully wetted. There is an optimal groove depth corresponding to a given droplet parameter, groove width and stud size that gives the best heat transfer rates. The wall temperature increase and the temperature fluctuations are small in the boiling regime as the power increases for the micro-structured surfaces.

1. Introduction

Spray cooling with phase change has received much attention in the past two decades and has been extensively promoted for removal of high heat fluxes in electronic systems and other high heat flux applications due to its high heat dissipating capability with low coolant mass fluxes at low wall superheats, its precise temperature control, low cost and reliable long-term stability. Heat fluxes in excess of 1000 W/cm^2 have been reported using water spray cooling at low coolant flow rates [1].

Spray cooling on smooth surfaces has been widely investigated. Chen et al. [2] experimentally studied the effects of various spray parameters such as the mean droplet size, droplet flux, and droplet velocity on the CHF and the efficiency of liquid usage, η, and found that the mean droplet velocity had the dominant effect on the CHF, followed by the mean droplet flux. Estes and Mudawar [3] and Rybicki and Mudawar [4] reported that the volumetric flux and the Sauter mean diameter were the key hydrodynamic parameters that influenced the spray cooling performance. The effects of subcooling [5], non-condensibles [6], orifice-to-nozzle distance [7] and inclination angle [8] have also been investigated.

Spray cooling on enhanced surfaces has been recently investigated to further enhance the heat transfer. Silk et al. [9] machined macro (mm) scale cubic pin fins, pyramids, and straight fins on a copper surface and studied their effects on the spray cooling heat transfer. The straight fins had the largest heat flux enhancement relative to the flat surface, followed by the cubic pin fins and the pyramids. Hsieh and Yao [10] performed water spray cooling experiments on plain and three micro-structured silicon surfaces with a smallest stud size of 160 μm and a smallest groove width of 120 μm and found that the Bond number of the microstructures is the primary factor responsible for the spray cooling heat transfer enhancement. The authors also divided the spray cooling on micro-structured surfaces into four distinct regions with different liquid film distribution patterns in the flooded region, the thin film region, the partial dryout region and the dryout region. Spray cooling experiments by Sodtke and Stephan [11] showed that spray cooling on micro scale pyramid structured surfaces lead to significantly better heat transfer performances than on smooth surfaces due to an increased length of the three phase contact line that forms on the structures which leads to very efficient thin film evaporation. Spray cooling on three microcavity surfaces and a flat surface was examined by Yang et al. [12] with the results showing that the heat transfer on the microcavity surfaces was much better than on the flat surface at high surface superheats once the heat transfer was dominated by nucleate boiling. Zhang et al. [13] also

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Nomenclature

G	groove width, μm	Q_{elec}	total electrical heat source on the silicon, W
S	stud size, μm	Q	heat dissipated by the spray, W
D	groove depth, μm	D_{10}	average diameter, μm
T_W	silicon top surface temperature, °C	D_{32}	Sauter mean diameter, μm
T_{Pt}	platinum temperature, °C	v	droplet velocity, m/s
T_f	water temperature, °C	A_S	stud top surface area directly impinged by the water spray, mm^2
$\bar{T}$	average temperature in an x cross section of the silicon, °C	A_B	base area, 7.4 mm × 7.4 mm
q	heat flux, W/cm^2	A_T	total area of the micro-structured surface, mm^2
h	heat transfer coefficient, W/(m^2 °C)	A_S/A_B	directly impinged surface percentage
H	silicon thickness, μm	A_T/A_B	area enhancement factor compared to the smooth surface
L	length, μm	*Superscripts*	
ε	volume fraction, $\varepsilon_i = L_i/(L_h + L_{uh})$	h	heated
λ	thermal conductivity, W/(m °C)	uh	unheated
R_{100}	standard resistance, Ω	c	critical
R_x	platinum resistance, Ω	0	silicon bottom conditions
U_{100}	standard resistance voltage, V	si	silicon
U_x	platinum voltage, V	s	loss
Q_x	electrical heat source in the platinum in each cell, W		

reported that the heat transfer enhancement on enhanced surfaces compared with flat surfaces and that enhanced surfaces with smaller feature sizes had better heat transfer rates. Moreover, Bostanci et al. [14] investigated a set of optimized enhanced surfaces, including micro-scale indentations and protrusions, macro-scale pyramidal pin fins, and multi-scale structured surfaces and found that one multi-scale structured surface and one micro-structured surface had the highest CHF of 910 W/cm^2, corresponding to an 18% increase over the reference smooth surface.

The characteristic sizes of most of the enhanced surfaces described in the literature have been greater than 100 μm; thus, the heat transfer on enhanced surfaces with smaller sizes still needs to be explored. The liquid film will spread better with smaller characteristic sizes as a result of stronger capillary forces; however, the micro-structures may be too small for the liquid to penetrate and flow freely which will reduce the advantages of the enhanced surfaces [10]. Hence, the heat transfer rates will be related to the enhanced surface characteristic size and the droplet parameters with few such studies known to the authors. The primary objective of the current study is to investigate the spray cooling heat transfer on one smooth and twelve enhanced silicon surfaces with micro-structures (characteristic sizes of 25 – 200 μm) with accurate measurements of the spray droplet parameters using the shadowgraph technique to explain the heat transfer mechanism.

2. Experimental system and parameter measurements

2.1. Experimental system

The spray cooling system shown in Fig. 1 included spray, heating and measurement sections. Deionized water driven by a Fluid-o-Tech magnetic drive gear pump flowed from the constant temperature water bath through the filter to remove impurities before being sprayed on the heated surface through a full cone pressure atomizer (Spraying Systems, TG SS 0.3) with a nozzle orifice of 0.51 mm. The nozzle was fixed in a bracket with the orifice-to-surface distance adjusted by an accurate micrometer with a positioning accuracy of 0.01 mm. A mechanical pressure gauge was used to measure the nozzle inlet pressure which was assumed to be equal to the spray pressure with one OMEGA 0.125 mm diameter T-type thermocouple imbedded in the flow tube just before the nozzle to measure the deionized water temperature. A flow rate measurement container with a square hole the same size as the heated surface was made to measure the water flow rate impinging the target surface as in reference [15].

The heating section was made of silicon dies. Various size micro-studs were fabricated on the top surface of the double-side polished, 490 μm thick silicon wafer by deep reactive ion etching (DRIE). Platinum was applied to the bottom surface of the silicon using positive photoresist lift-off in a serpentine pattern with a thickness of approximately 216 nm. The platinum was used both as the heat source and the resistance thermometer to measure the bottom surface temperature that was extracted to the silicon top surface temperature. The platinum temperature was found from its linear resistance–temperature relationship over a wide temperature range with high repeatability and its chemical stability. The wafer was then cut into several 7.4 mm × 7.4 mm dies.

Four platinum resistors were designed on the bottom surface of each silicon die to reduce the voltage input for safety considerations with each platinum resistance being 400–500 Ω. The silicon die was mounted on a temperature resistant PCB circuit board and eight 40 μm gold wires connecting the four platinum resistors with the circuit board by wire bonding. A DC stabilized voltage source was then used to supply power to the platinum through eight wires soldered on the circuit board. A synthetic glass sleeve filled with calcium silicate cellucotton (thermal conductivity = 0.05 W/m K) was glued to the bottom of the circuit board to reduce the heat losses. The system was considered to be at steady state after the voltage and the temperature remained constant for at least 15 min with the results calculated using the last 5 min.

2.2. Temperature measurement method

The relationship between the temperature and the platinum resistance was calibrated before the spray experiments in a HART SCIENTIFIC 6022 water bath with thermostatic control for every 5 °C between 25–85 °C with a precision of 0.01 °C. The heat flux uniformity in the silicon was guaranteed by the serpentine platinum heaters on the bottom surface which were very closely spaced, and platinum heaters with widths of 100 μm and spacings