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Spray cooling of enhanced surfaces: Impact of structured surface geometry and spray axis inclination

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Abstract

Experiments were conducted to study the effects of enhanced surfaces and spray inclination angle (the angle between the surface normal and the axis of symmetry of the spray) on heat transfer during spray cooling. The surface enhancements consisted of cubic pin fins, pyramids, and straight fins. These structures were machined on the top surface of heated copper blocks with 2.0 cm^2 cross-sectional areas. Measurements were also obtained on a heated flat surface to provide baseline data. PF-5060 was used as the working fluid. The spray was produced using a 2×2 nozzle array under nominally degassed conditions (chamber pressure of 41.4 kPa) with a volume flux of 0.016 m^3/m^2 s and a nozzle height of 17 mm. The spray temperature was 20.5 °C. For the geometries tested, the straight fins had the largest heat flux enhancement relative to the flat surface, followed by the cubic pin fins and the pyramid surface. Each of these surfaces also indicated an increase in evaporation efficiency at CHF compared to the flat surface. Inclination of the spray axis between 0° and 45° relative to the heater surface normal created a noticeable increase in heat flux compared to the normal position (0° case). A maximum heat flux enhancement of 23% was attained for the flat surface. The straight finned surface had a maximum heat flux enhancement of 75% at an inclination angle of 30° relative to the flat surface in the normal position. However, only a marginal increase ($\sim$11%) was observed in comparison to the straight finned surface in the normal position (0° case).

Keywords: Enhancement; Spray cooling; Finned surfaces; Heat transfer

1. Introduction

1.1. Background

NASA's new vision for space exploration encompasses the development of alternative power systems and advanced on-board flight system components such as laser–diode arrays (LDA's) and multi-chip modules (MCM's). Thermal management of these systems is critical to mission success. Projected thermal control requirements include high heat flux cooling capability ($\geqslant 100$ W/cm^2), tight temperature control (approx +/−2 °C), reliable (on demand) start-up, shut down, and long term stability. Traditional multiphase thermal control flight technologies (loop heat pipes, capillary pumped loops, etc.) satisfy the temperature control and stability requirements, but their heat flux removal capabilities are limited. Spray cooling can provide high heat fluxes in excess of 100 W/cm^2 using fluorinerts and over 1000 W/cm^2 with water while allowing tight temperature control at low coolant fluid flow rates. It is a proven flight technology that has been demonstrated through the Space Shuttle's open loop flash evaporator system (FES). Provided closed system issues such as scavenging excess liquid and vapor can be adequately resolved, spray cooling presents one of the most appealing heat transfer techniques for the thermal management needs of tomorrow's high heat flux space platforms. As with any

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Nomenclature

A	area
H	structure height
L	distance between successive structures
P	pressure
R_a	surface roughness
R_{fl}	$\frac{(T_{surf}-T_l)}{\dot{q}''}$, convective thermal resistance
T	temperature
TC	thermocouple
X	structure feature dimension
c_p	specific heat
h	convection coefficient
h_{fg}	enthalpy of vaporization
k	conductivity
$\dot{m}$	mass flow rate
p	structure pitch
$\dot{q}''$	heat flux per unit area
u	uncertainty
x	distance from heater surface within heater
ΔP	pressure across nozzle
Γ	weighted volume flux for concentric ring
$\delta\dot{q}''$	error in heat flux
δ_k	error in conductivity
$\delta_{\Delta T}$	error in thermocouple temperature difference
δ_x	error in thermocouple location
η	evaporation efficiency
ξ	area utilization factor, $(q''_{surf}/q''_{flat})/(A_{surf}/A_{flat})$

Subscripts

flat	flat surface
i	concentric ring
k	conductivity
l	liquid
CHF	critical heat flux
max	maximum
sat	saturation conditions
surf	surface
T	temperature
x	thermocouple distance
$1-\Phi$	single phase
$2-\Phi$	multiphase

emerging thermal management technology, finding ways to increase the thermal performance through passive enhancement mechanisms can offer substantial benefits, and is the focus of the current work.

1.2. Literature review

1.2.1. General studies

Many research efforts have been performed to gain a better understanding of the phenomena and critical parameters associated with spray cooling heat transfer. A review of the literature shows that previous studies have parametrically examined the effect of secondary gas atomizers vs. pressure atomizers [1,2], mass flux of ejected fluid [3,4], spray velocity [5,6], surface impact velocity [5–8], microscale surface roughness [1,6,9,10], ejected fluid temperature [11], chamber environmental conditions [11], and spray footprint optimization on the effective heat flux across the heater surface [11]. Other topics researched to date include the effect of surfactant addition [12,13], secondary nucleation [1,14,15] and dissolved gas effects [16].

1.2.2. Surface roughness

Spray cooling is considered a multiphase convective process, and is subject to traditional heat transfer enhancement techniques that are typically applied to convective heat exchange surfaces. While the Space Shuttle's FES used cyclic water spray cooling of enhanced surfaces (triangular grooves) to cool freon based heat exchangers [17], overall work in the area of spray cooling with enhanced surfaces has been very limited. Most previous studies that have examined enhanced surfaces have done so primarily from the perspective of surface roughness. Sehmbey et al. [1] gives an overview of spray cooling and provides a comparison of its effectiveness when using liquid and secondary gas atomizers (air used as the secondary gas). Heat flux was measured and presented for both techniques. It was found that the heat transfer coefficient increased with the use of smooth surfaces ($R_a < 0.1$ μm) for gas atomized sprays, while the opposite trend was observed for liquid atomized sprays. Both the heat flux and the convection coefficient were found to have comparable values for both atomizer types. The authors concluded that the most important parameters affecting heat transfer were the fluid properties, spray velocity, and surface roughness.

Pais et al. [10] studied the effects of surface roughness (values ranged 0.3–22.0 μm) on heat transfer when using spray cooling. The sprayed surface was copper with a projected area of 1 cm^2. An air-assist atomizing nozzle was used with deionized water as the working fluid. Tests were conducted at a nozzle height of 23 mm. It was found that the 0.3 μm surface achieved the highest heat flux, with a peak heat flux of 1250 W/cm^2. The onset of nucleate boiling also occurred at lower superheat values. The authors attributed the heat transfer enhancement to early bubble departure from the surface during nucleate boiling, and concluded that secondary nucleation has a primary role as a heat transfer mechanism only if the surface finish is smooth.

1.2.3. Enhanced surface pool boiling

Much work has been performed on pool boiling using enhanced surfaces. Surface modifications previously investigated include the use of paints, porous structures, and structured surface geometries (submicron, micro, and