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Experimental investigation of spray cooling on flat and enhanced surfaces

Zhen Zhang [a,b], Jia Li [a,b], Pei-Xue Jiang [a,b,*]

[a] Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Department of Thermal Engineering, Tsinghua University, Beijing 100084, PR China
[b] Beijing Key Laboratory of CO_2 Utilization and Reduction Technology, Department of Thermal Engineering, Tsinghua University, Beijing 100084, PR China

HIGHLIGHTS

- ► Differences between spray cooling on flat and enhanced surfaces were investigated.
- ► The shadowgraph technique was used to accurately measure the droplet parameters.
- ► Heat transfer was enhanced for the enhanced surfaces compared with the flat surface.
- ► There is an optimal flow rate and optimal orifice-to-surface distance.
- ► The heat transfer increased with the surface roughness.

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ABSTRACT

The heat transfer during spray cooling was studied experimentally using deionized water to investigate the effects of the spray characteristics, flat and enhanced surfaces with micro-structures and the surface roughness on the heat transfer. The shadowgraph technique was used to measure the droplet parameters with the results showing that the droplet sizes decreased while the velocities and droplet number density increased as the flow rate increased. The spray cooling experiments further showed that the heat transfer was enhanced in both the single and two phase regions for enhanced surfaces compared with the flat surface and that the enhanced surface with smaller feature sizes had better heat transfer rates. Thus, the enhanced surface effectively improves the spray cooling heat transfer. There is an optimal flow rate and optimal orifice-to-surface distance for spray cooling on both flat and enhanced surfaces, with the optimal flow rate increasing and the optimal orifice-to-surface distance decreasing as the groove size decreases. The heat transfer performance is best for a spray inclination angle of 0° and the heat transfer rate increases with surface roughness.

1. Introduction

Numerous industrial applications require the removal of high heat fluxes, such as electronic systems, high-power lasers, energy weapons and aerospace satellite. Zhirnov et al. [1] stated that even if entirely different electron transport models are developed for digital circuits, their density and performance scaling may not go much beyond the ultimate limits obtainable with CMOS technology, due primarily to limits on the heat removal capacity. Phase change cooling technologies are the obvious choices for such problems, including jet impingement, spray cooling, micro-channel flows and thermosyphon cooling, with the first two of the greatest interest [2]. Spray cooling is one of the best solutions due to its high heat dissipating capability with low coolant mass fluxes at low wall superheats, precise temperature control, low cost and reliable long-term stability. Yang et al. [3] suggested that the heat fluxes could exceeded 100 W/cm^2 with fluorinerts and 1000 W/cm^2 using water at low coolant flow rates.

Spray cooling has been widely investigated. NASA has investigated spray cooling in collaboration with the Air Force for earth science satellites and the crew exploration vehicle [4]. Tests on dual Opteron Compact PCI computers demonstrated that spray cooling reduced the junction temperature by 33 °C with a 35% power consumption reduction compared to air cooling [5]. Bostanci et al. [6] developed a spray cooling system for thermal management of power inverter modules used in automotive applications and

* Corresponding author. Department of Thermal Engineering, Tsinghua University, Beijing 100084, PR China. Tel.: +86 10 62772661; fax: +86 10 62770209.
E-mail address: jiangpx@mail.tsinghua.edu.cn (P.-X. Jiang).

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Nomenclature

x	thermocouple position, m
λ	thermal conductivity, W/m K
q	heat flux, W/cm^2
h	heat transfer coefficient, W/cm^2 K
D_{10}	droplet average diameter, μm
V	droplet velocity, m/s
D	target surface diameter, m
G	mass flux sprayed directly onto the surface, kg/m^2 s
Re	Reynolds number, $Re = GD/\mu$
Nu_D	Nusselt number, $Nu_D = hD/\lambda$
T_w	wall temperature, °C
T_{sat}	water saturation temperature, °C

observed that two simulated devices had heat fluxes of up to 200 W/cm^2 with only 14 °C surface superheat. Tests performed with hybrid vehicle electronics showed that spray cooling could dissipate 150–200 W/cm^2 while maintaining the chip temperature below 125 °C, with HFE-7100 identified as the optimum coolant in all performance categories [7]. In addition, Aguilar et al. [8–10] showed that spray cooling was useful for spatially selective cooling of human skin to rapidly dissipate heat during dermatologic laser surgery.

Numerous investigations have been done on spray cooling on flat surfaces. Chen et al. [11,12] studied the effects of the droplet parameters such as the mean droplet size, droplet flux and droplet velocity on the critical heat flux and found that the mean droplet velocity had the greatest effect on the CHF and the heat transfer coefficient at CHF, followed by the mean droplet flux. The Sauter mean diameter did not appear to affect the CHF. Many researchers have studied the effects of coolant subcooling, flow rate, orifice-to-surface distance and spray inclination angle [2,13–16].

Spray cooling on enhanced surfaces has been recently investigated to further enhance the heat transfer. Silk et al. [17] studied spray cooling with three enhanced surfaces having cubic pin fins, pyramids and straight fins and found an increase in the evaporation efficiency at CHF compared to a flat surface with the straight finned surface having the greatest heat flux enhancement. Hsieh and Yao [18] evaluated the evaporative heat transfer characteristics of spray cooling of water on plain and micro-structured silicon surfaces at very low spray mass fluxes. They pointed out that the Bond number of the microstructures was the primary factor responsible for the spray cooling heat transfer enhancement and that the micro-structured surfaces provided better cooling performance in the thin film and partial dryout regimes with higher liquid film breakup heat fluxes because more water was retained on the heat transfer surface by the capillary forces. Sodtke and Stephan [19] observed that spray cooling on a micro-structured surface significantly improved the cooling rates compared to smooth surfaces at the same wall superheat and that this effect was due to an increased length of the three phase contact line that formed on the structures which increased the thin film evaporation rate. Coursey et al. [20] explored spray cooling of high-aspect-ratio open microchannels and showed that all five enhanced surfaces had better heat transfer rates than a flat surface. In addition, Alvarado [21] tested spray cooling on a nanostructured surface and found a more uniform temperature profile at and near the impact area with a lower minimum wall temperature especially at higher heat fluxes.

However, the effects of the spray characteristics on enhanced surfaces and the differences in the spray characteristics between spray cooling on a flat surface and on an enhanced surface have attracted limited attention. The primary objective of the current study is to investigate spray cooling heat transfer on a flat surface and three enhanced surfaces and the effects of liquid flow rate, orifice-to-surface distance and spray inclination angle on the heat transfer. The effect of the surface roughness on the heat transfer is also investigated for Sa roughnesses ranging from 142 to 2258 nm. The shadowgraph technique is used to accurately measure the spray droplet parameters to explain the heat transfer mechanism.

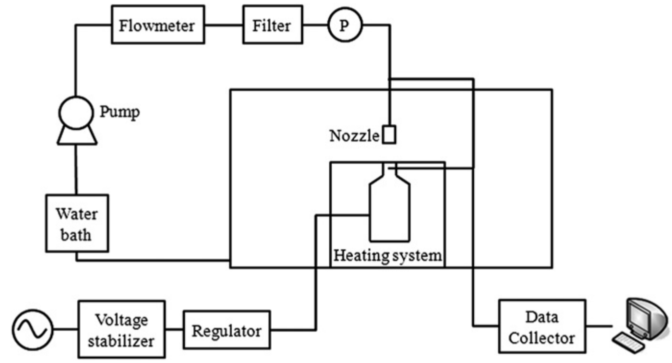

Fig. 1. Spray cooling equipment system drawing.

2. Experimental system

The spray cooling experimental system shown in Fig. 1 included the spray, heating and measurement sections. Deionized constant temperature water was driven by the pump from the water bath and through the filter to remove impurities before being sprayed on the heated surface through the nozzle.

The nozzle was a PNR full solid cone, BCQ 0740 T1, with a nozzle orifice diameter of 1.0 mm. The nozzle was fixed in a bracket with the orifice-to-surface distance adjusted using an accurate micrometre with a positioning accuracy of 0.01 mm. A Fluid-o-Tech magnetic drive gear pump with an MGC11 motor and an MG204XPS17 pump head was used to pump the deionized water at flow rates from 20 L/h to 70 L/h. The thermostatically controlled water bath was model DKB-2015 with a temperature range of 0–99 °C and temperature fluctuations of ±0.1 °C. One OMEGA 0.125 mm diameter T-type thermocouple was imbedded in the flow tube just before the nozzle to measure the deionized water temperature.

The heater was made of a copper block heated by a sleeve heater. The copper block was a 40 mm diameter, 80 mm tall cylinder, tapered near the top to a 12 mm diameter, 10 mm tall cylinder. The power was controlled by a voltage regulator. The heater was surrounded by calcium silicate cellucotton (thermal

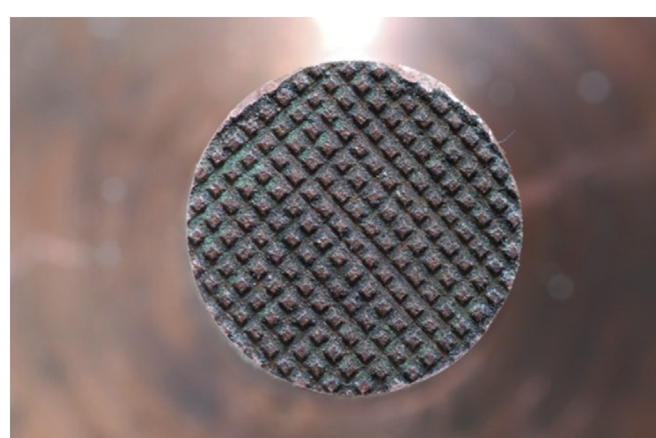

Fig. 2. Enhanced surface S1.