International Journal of Heat and Mass Transfer 80 (2015) 26–37

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Experimental investigation of spray cooling on micro-, nano- and hybrid-structured surfaces

Zhen Zhang [a,b], Pei-Xue Jiang [a,*], David M. Christopher [a], Xin-Gang Liang [c]

[a] Key Laboratory for Thermal Science and Power Engineering of the Ministry of Education, Department of Thermal Engineering, Tsinghua University, Beijing 100084, PR China
[b] Institute of Nuclear and New Energy Technology, Tsinghua University, Beijing 100084, PR China
[c] Key Laboratory for Thermal Science and Power Engineering of the Ministry of Education, School of Aerospace Engineering, Tsinghua University, Beijing 100084, PR China

ARTICLE INFO

Article history:
Received 28 May 2014
Received in revised form 27 August 2014
Accepted 30 August 2014
Available online 26 September 2014

Keywords:
Spray cooling
Micro-
Nano-
Hybrid-structured surface
Local thermal non-equilibrium model

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 a smooth silicon surface and micro-, nano- and hybrid micro/nano-structured surfaces. The spray cooling experiments show that the heat transfer rates were better for the nano-structured surface, followed by the smooth surface coated with the SiO_2 film and the pure silicon surface since the contact angle was smallest on the nano-structured surface and increased on the latter two. The droplet parameter results show that most droplets were 40–60 μm in size. The heat transfer coefficient increased and the wall temperature decreased on the 25G × 25S surface coated with the SiO_2 film compared with the 50G × 50S surface coated with the SiO_2 film as the heat transfer moved into the partial dryout region due to the SiO_2 film's stronger hydrophilicity so the heated area was more fully utilized, while the CHF was larger for the 50G × 50S surface. Coating the micro-structured surfaces with carbon nano-tube (CNT) films having characteristic sizes smaller than the droplet size was more effective than on the surfaces with larger characteristic sizes. The CHF was largest on the 25G × 25S surface coated with 4 carbon nano-tube films with a 75.3% increase over the smooth surface. The wall temperature increase and the temperature fluctuations were small in the boiling regime as the power increases for the enhanced surfaces.
© 2014 Elsevier Ltd. All rights reserved.

1. Introduction

Numerous industrial applications, such as electronic systems, high-energy lasers, energy weapons and aerospace satellites, have substantial need for more effective thermal management. Spray cooling, with its high heat dissipating capability, has been playing an important role in high heat flux applications as one of the most effective thermal management methods. Heat fluxes in excess of 1000 W/cm^2 have been reported using water spray cooling at low coolant flow rates [1].

Spray cooling heat transfer is influenced by many factors such as the droplet parameters [2], working fluid [3], nozzle-to-surface distance and inclination angle [4,5], so it has been widely investigated by researchers in the past two decades. Surface morphology is another critical effect for spray cooling heat transfer enhancement. Enhanced surfaces, such as milli-structured surfaces [6], micro-structured surfaces [7,8] and microcavity surfaces [9,10] have been shown to effectively improve the heat transfer.

Spray cooling heat transfer on smooth and micro-structured surfaces (characteristic sizes of 25–200 μm) has been studied in detail in previous research in this group [11] with the results showing that micro-structured surfaces effectively increased the spray cooling heat transfer rates in the thin film and partial dryout regions. The effects of the groove width and stud size on the heat transfer were correlated with the droplet parameters. The micro-structured surface with larger characteristic sizes had a smaller area enhancement factor and worse heat transfer rates, while 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. However, the spray cooling heat transfer on nano- or hybrid micro/nano-structured surfaces is not clearly understood and the literature has few studies on their effects to the authors' knowledge.

Only Alvarado [12] has investigated spray cooling on nano-structured surfaces and observed lower minimum wall temperatures for similar heat fluxes, better heat transfer curves, and lower temperature gradients on the nano-structured surfaces than on the bare surface. Nano-structured surfaces have also been used for

* Corresponding author. Tel.: +86 10 62772661; fax: +86 10 62775566.
E-mail address: jiangpx@tsinghua.edu.cn (P.-X. Jiang).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.08.085
0017-9310/© 2014 Elsevier Ltd. All rights reserved.

Nomenclature

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

Superscripts

h	heated
uh	unheated
c	critical
0	silicon bottom conditions
si	silicon
s	loss

pool boiling with the results helping understanding of the spray cooling heat transfer on such surfaces. Young Lee et al. [13] investigated the nucleate pool boiling heat transfer and long-term performance of a nano-porous surface fabricated by anodizing with the results showing that the nucleate boiling heat transfer coefficient of the nano-porous coating surface was higher than that of the non-coated surface particularly at low heat fluxes with higher heat transfer coefficients remaining throughout 500 h of operation. Im et al. [14] fabricated copper nanowire arrays on a silicon substrate by electro-chemical deposition and observed that the copper nanowires increased the pool boiling Critical Heat Flux (CHF) and reduced the wall superheat compared to a smooth silicon surface. An optimum CHF was found at a nanowire height of 2 μm. Kwark et al. [15] found that a nanoparticle coated heater consistently produced dramatic CHF enhancement relative to an uncoated surface for all tested conditions. The authors postulated that the better wettability in the nanocoating was the main cause of the enhancement. Thus, all the experiments show that the nano-structures on the surface improve the heat transfer rates.

In addition, hybrid micro/nano-structured surfaces have been used in pool boiling to further enhance the heat transfer in recent years. Various micro-, nano- and hybrid-structures were fabricated on copper surfaces with the corresponding pooling boiling heat transfer performance studied by Li et al. [16]. The authors claimed that the CHF of the hybrid-structured surfaces was about 15% higher than that of the surfaces with nanowires only and micro-pillars only, and that the superheat at CHF for the hybrid-structured surface was about 35% smaller than that of the micro-pillared surface. Launay et al. [17] studied pool boiling on smooth, nano-, micro- and hybrid-structured surfaces using PF5060 and water. The highest heat fluxes were obtained using the 3D microstructures without CNTs and the experimental results indicate that the heat transfer rates were higher on the purely nano-structured interfaces only at very low superheats compared to the smooth surfaces, but still lower than those on the conventional Si-etched microstructures for all cases.

The primary objective of the current study is to investigate spray cooling heat transfer on smooth and nano-, micro- and hybrid-structured surfaces 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 Co.) 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. The experiments used a water spray pressure of 0.3 MPa with an orifice-to-surface distance of 30 mm with subcoolings of −82 to −80 °C. 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 Ref. [11]. The flow rate was 1.239 kg/m^2 s in all cases.

The heating sections were made of 7.4 mm × 7.4 mm, double-side polished, 490 μm thick silicon dies. One CNT film or four CNT films laid in the cross direction with tube diameters of 80–90 nm were laid on the top surface. Then, Plasma Enhanced Chemical Vapor Deposition (PECVD) was used to deposit a SiO_2 film having a thickness 50 nm on the CNT films to prevent the nanotubes from being washed away by the spray. These surfaces are referred to as nano-structured surfaces. A smooth surface having just a 50 nm thick SiO_2 film, called the SiO_2 film surface, was used to study the wettability effect in comparison with the smooth surface and to study the nano-scale structures effect compared with the nano-structured surfaces.

A three-dimensional white light surface interference profilometer was used to measure the roughnesses of the smooth surfaces with a resolution of 752 × 489 pixels, RMS repeatability precision of 1 nm and calibration accuracy ≪ 0.1%. Sa was defined as the average difference in the profile height from the average height within the sample length, which is widely used to characterize

Download English Version:

https://daneshyari.com/en/article/657244

Download Persian Version:

https://daneshyari.com/article/657244

Daneshyari.com