International Journal of Heat and Mass Transfer 121 (2018) 832–844

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Microspray quenching on nanotextured surfaces via a piezoelectric atomizer with multiple arrays of micronozzles

Shou-Shing Hsieh *, Wei-Che Chang

Department of Mechanical and Electromechanical Engineering, National Sun Yat-Sen University, Kaohsiung 80424, Taiwan, ROC

ARTICLE INFO

Article history:
Received 9 August 2017
Received in revised form 10 January 2018
Accepted 11 January 2018
Available online 7 March 2018

Keywords:
Microspray quenching
Piezoelectric atomizer
Graphene thin film roughened surface

ABSTRACT

We present an experimental study on heat transfer characteristics with the goal to enhance the cooling performance of a water spray impinged on smooth, polished copper surfaces and three different types of nanotextured surfaces with different thicknesses of diamond-like carbon (700 and 1000 nm), multi-wall carbon nanotube (50, 100 and 150 nm), and graphene nanotextured surfaces (1, 2, 5, and 10 nm). A multiple spray was produced by a commercial piezoelectric (PZT) actuator (power = 1.5 W and frequency 104 kHz) with a nozzle hole size of $d_j = 35\ \mu m$ and a corresponding mass flow rate of 5.33×10^{-4} kg/s at a spray height of 50 mm. Relevant data for both the transient and steady state boiling heat transfers (BHT), as well as the quench tests were obtained and discussed. Furthermore, the effect of the nanotextured surface thickness on cooling performance was extensively examined. Results indicated that the nanotextured surfaces enhanced the spray cooling performance mainly due to the improved wettability and liquid spreading that they provided especially for graphene thin films. A somewhat high critical heat flux (CHF) of nearly 310 W/cm^2 (the corresponding heat transfer coefficient, HTC $\approx$ 3 W/cm^2 K) under a specific working condition for graphene thin-film surfaces with 1 nm thickness was found. Furthermore, the thermal conductivity effect was also noted and significant influence on BHT and CHF was found for graphene nanotextured surfaces.

1. Introduction

Spray cooling and/or quenching have proven to be efficient and powerful methods for the removal of high heat fluxes with various and wide industrial and medical applications, such as fire extinguishing, cryogenic dermatological cooling, and cooling of high performance electronic devices. Spray cooling and quenching have a high heat transfer, a small coolant inventory, uniformity of heat removal, a low superheat, and no thermal resistance with heating surfaces among the realistic heat dissipation methods, such as forced convection/flow boiling in a microchannel heat sink, heat pipe or vapor chambers, and jet impingements [1–3]. Despite the merits and advantages stated above, due to the dramatic increase in the use of advanced electronic applications, there is still a need to improve spray cooling heat transfer for modern electronic systems, especially for miniature and microelectronic devices.

The heat transfer coefficient (HTC) during spray cooling heat transfer is controlled not only by the temperature difference between the impinged spray and the target surface but also by the characteristics of the spray itself, which include a number of parameters of the nozzle type, spray height, spray angle, working fluid, droplet size and distribution, and target surface conditions. In addition, the complexities associated with the spray impingement process onto a target surface with a specific micro/nanostructure and the resultant thermal response are not yet fully understood.

Surface enhancement in terms of porous and rough surfaces has long been recognized as an effective means to increase the heat transfer rate for numerous industrial applications. This is because they can cause an increased nucleate site density which improves the boiling heat transfer (BHT). Therefore, spray cooling over a micro/nanostructured surface may also improve the heat transfer. Sodtke and Stephan [4] and Ndao et al. [5] found that spray cooling on the surface of straight fins, cubic pin fins, and pyramids would consistently increase the critical heat flux (CHF). Micro/nanostructured surfaces have also been studied to examine their influence on thermal performance. Hsieh et al. [6] reported a spray cooling performance enhancement of 610 W/cm^2 with a 50 μm diamond thin-film and a low mass flow rate of 2.92×10^{-4} kg/s to 17.85×10^{-4} kg/s. Zhang et al. [7] experimentally studied spray cooling heat transfer using DI water to examine the spray characteristics and differences between the smooth surface and 12 enhanced surfaces.

---

* Corresponding author.

E-mail addresses: sshsieh@faculty.nsysu.edu.tw (S.-S. Hsieh), m023020103@student.nsysu.edu.tw (W.-C. Chang).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.01.044
0017-9310/

Nomenclature

A_s	heater's surface area, cm^2
C_p	specific heat, kJ/kg K
D_j	diameter of nozzle hole, μm
H	spray height, mm
H	local heat transfer coefficient, W/m^2 K
H_{avg}	average heat transfer coefficient, W/m^2 K
m	total mass flow rate, kg/s
Q_1	total heat transfer rate, W
Q_2	heat loss, W
q''	heat flux, W/cm^2
T	heater's center surface temperature, K
T_a	ambient temperature, K
T_s	saturation temperature, K
T_w	heater's average surface temperature, K
t	time, s
um	measured spray velocity at the nozzle (single) exit, m/s
x, y, z	coordinates, m

Greek symbols

ρ	density of liquid, kg/m^3
σ	surface tension, N/m
μ	viscosity of liquid, N s/m^2
ΔT_l	T_w-T_l
ΔT_s	T_w-T_s
δ	nanotextured surface thickness, nm

Subscripts

avg	average
CHF	critical heat flux
cu	copper
j	nozzle exit
l	liquid
m	measured
s	saturation/smooth
w	wall

Nanotextured/microstructured surfaces have been proven to have the capability to meet future challenges of heat dissipation/removal for microelectronic cooling used in very limited/compact spaces because the nanotextured surfaces can increase the surface area, and incidentally, generate a number of small pores that enhance the boiling heat transfer (BHT). Many nanotextured/microstructured networks can be found by using conventional deposition techniques. Graphene film is one of them, typically having the form of ultra-thin microscale flakes with a two-dimensional honeycomb monolayer. It has received considerable attention mainly due to its large capacity for thermal conductivity and high transparency, which seem to be good for heat removal. It was found that the cooling performance was improved with microstructured surfaces under certain boiling conditions.

Advanced microfabrication processes have led to many creative ideas and innovations in spray atomization and its related technologies. Therefore, the technique of atomization and the resultant spray flight profiles seem quite diverse depending on the choice of the nozzle type and the atomization mechanism. One pressure atomization can be accomplished by using a piezoelectric ultrasonic ring actuator with multiple arrays of micronozzles by which a circular spray can be created through a full cone where most of the droplets' coverage is along its circumference. Moreover, as electronic packing becomes more compact and the electronic devices' power continues to increase, more efficient heat dissipation, especially for a much smaller space, becomes quite challenging. Again, the selection of a nozzle type, with auxiliary components as well as cooling technology, is very crucial. Due to its relative advantages of high speed, high flow rate, low power consumption, simple structure, and compactness, compared to those of its competitors, the PZT actuated ultrasonic atomizer has been widely used in inkjet printing, painting, and medical care for droplet generation [10]. However, its application in spray cooling for power electronic devices is quite limited [9].

In view of the foregoing discussions, it appears that nanotexturing is promising for cooling enhancement. In the present study, we report an experimental work with three different materials with nanotextured films of diamond-like carbon (700 nm, 1000 nm), multi-walled nanotubes (50 nm, 100 nm, 150 nm), and graphene (1 nm, 2 nm, 5 nm, 10 nm) in a variety of thicknesses.

2. Experiments

Fig. 1 shows the proposed closed loop of the present water spray system which includes (1) a PZT actuator-assisted spray atomization with multiple arrays of microholes, (2) an oxygen-free copper plate heater with/without a thin film nanotextured surface as a target surface, and (3) a spray chamber and data acquisition system. Some related experimental parameters are listed in Table 1.

2.1. Nanotextured surface preparation

The modified surfaces of the present study are shown in Fig. 2. They are diamond-like carbon (DLC), MCNT (multi-walled carbon nanotube), and graphene thin film, respectively. The substrate material of the enhanced surfaces is a copper plate (sheet). Except for the graphene thin film, which was made through physical vapor deposition (PVD), the nanotextured surfaces were made via chemical vapor deposition (CVD). One of the typical geometric sizes for each type of surface roughness is listed in Table 2 in which both SEM and AFM surface characterizations were made. The associated SEM surface topography proves that good smoothness was still found for three of the different modified surfaces compared to that of the polished copper surface. The nanotextured surface morphology images of DLC, MCNT, and graphene films with smooth polished copper surfaces taken by AFM areal are shown in Fig. 2, with maximum roughness heights of 7.3 nm, 62.6 nm, 19.8 nm, and 12 nm, respectively. The related parameters and variables characterizing its surface conditions are also listed in Table 2 for reference. Furthermore, the contact angles of the DI water on the nanotextured surfaces under study were measured before and after the experiments, and it was found that the corresponding values were almost identical. The heat transfer performance of the aforementioned enhanced surfaces was measured or calculated and compared to that of a smooth polished surface.

2.2. Spray atomization system

A commercial lead zirconate titanate piezoelectric (PZT) actuator was used, functioning as an ultrasonic atomizer [9] from which deionized (DI) water spray could be issued out of approximately one thousand microholes with a definite d_j of 35 μm. A circular