International Journal of Heat and Mass Transfer 124 (2018) 307–318

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Water droplet impacting on overheated random Si nanowires

Manuel Auliano [a], Maria Fernandino [a], Peng Zhang [b], Carlos Alberto Dorao [a,*]

[a] *Department of Energy and Process Engineering, Norwegian University of Science and Technology, Trondheim 7034, Norway*
[b] *Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, Shanghai 200240, China*

ARTICLE INFO

Article history:
Received 5 January 2018
Received in revised form 1 March 2018
Accepted 13 March 2018

Keywords:
Leidenfrost
Si nanowires
Metal Assisted Chemical Etching
Impact
Low thermal conductivity

ABSTRACT

Micro and nanostructured surfaces can significantly improve the heat transfer capability and shift the Leidenfrost temperature of impacting droplets. In this study, the effect of overheated random Si Nanowires on impacting water droplets is presented. The cooling performance was studied in term of droplet evaporation time and surface temperature while the boiling dynamics was observed through high-speed visualization. The Si Nanowires can increase almost twice the Leidenfrost temperature compare to the similar case of plain Si surface. At the same time, the heat transfer is enhanced by widening the transition boiling region about 150 K. In this regime, the film liquid lift-off behavior is observed in the range of the We numbers studied.

1. Introduction

Nowadays the main technology bottleneck for several industrial applications such as electronics, aeronautics, and nuclear power is cooling for ultra-high heat flux devices [1]. The boiling phenomenon represents the most effective solution to this short-term challenge because of the large latent heat associated with the phase-change. The spray cooling is a cooling technique of increasing interest widespread in situations involving rapid cooling of overheated components [2]. When a droplet is hitting a heated surface, the cooling is effective as long as there is a contact of the liquid with solid surface.

The typical process is sketched in Fig. 1 where the different boiling regimes are illustrated. An accurate description of the phenomena involved in the boiling regimes is provided in [3]. Two characteristic points, i.e. the Critical Heat Flux (CHF) and the Leidenfrost Point (LFP) indicated respectively by red triangle and red square in Fig. 1, are important for an efficient and safe design of the thermal applications. At the CHF and the LFP, the heat transfer coefficient and the droplet lifetime reach respectively the peak value. At and above the Leidenfrost temperature, a continuous vapor layer hinders the contact between the droplet and the solid surface.

Hence, the heat transfer dissipation is deteriorated due to the low thermal conductivity of the vapor phase resulting in the potential burnout of the heated surface. Increasing the Leidenfrost point and shifting the evaporation curve towards shorter evaporation times will make the design of thermal management applications safer and more efficient respectively, therefore understanding the fundamental mechanisms governing this phenomenon will allow controlling the critical threshold of a specific surface. The occurrence of the film boiling regime depends on several parameters, such as surface temperature, droplet size, surface properties and impact velocity [4].

Recently research has been focused on controlling the heat transfer capability of the surface to droplets. In particular, this has been achieved by tailoring the surface with micro-nano structures in order to control the wettability and surface roughness [5–7]. In particular, an overview of previous research focused on surfaces coated with micro-nanostructures and its impact on the Leidenfrost point has been presented in [3]. Based on the understanding gained from the previous studies, Adera et al. (2013) concluded that greater attention should be paid to high-aspect ratio nanoscale structures with low thermal conductivity and low solid fraction for heat transfer applications that demand higher transition superheat [8].

Several studies on the effect of overheated high-aspect ratio nanostructures on impacting droplet have been reported. Srikar et al. (2009) coated the surfaces with electrospun non-woven polymer nanofiber mats [9]. The enhanced cooling rate was attributed to the suppression of the receding and bouncing of water droplets that allow exploiting completely the latent heat of evaporation. Sinha-Ray et al. observed water (2011) [10] and FC-7300 (2014) [11] droplet impact on polymer nanofiber mats covered with

---

* Corresponding author.
E-mail address: carlos.dorao@ntnu.no (C.A. Dorao).
URL: http://folk.ntnu.no/cadorao/ (C.A. Dorao).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.03.042
0017-9310/

Nomenclature

B	systematic uncertainty
Bi	Biot number
C	specific heat (J/kg/°C)
Ca	capillary length (m)
CA_{mean}	mean apparent contact angle (°)
D	droplet diameter (m)
DI	deionized
ΔT	temperature difference between droplet and wall
ΔT_{LFP}	LFP shift compared to the reference case (°C)
H	distance between the needle tip and the tested surface (m)
HTC	heat transfer coefficient ($W/(m^2\ K)$)
H_v	characteristic thickness of the vapor layer (m)
N_T	number of temperature samples recorded
N_t	number of impinged droplets
Nu	Nusselt number
P	random uncertainty
Pe	Peclet number
S	standard deviation
St	Stokes number
T	temperature (°C)
V	droplet volume (m^3)
We	Weber number
d	diameter (m)
g	gravity acceleration (m/s^2)
h	height (m)
h_{lv}	latent heat (J/kg)

k	thermal conductivity (W/m/K)
t	time (s)
t_v	value of the t-distribution
v	normal impact velocity (m/s)
w	total uncertainty

Greek symbols

α	thermal diffusivity (m^2/s)
ρ	density (kg/m^3)
τ	timescale (s)
μ	dynamic viscosity (Pa s)
σ	surface tension (N/m)

Abbreviations

CHF	Critical Heat Flux
LFP	Leidenfrost point
MaCE	Metal Assisted Chemical Etching
NWs	Nanowires

Subscripts

c	cooling
e	exposure to the vapor flow
h	heat transport
l	liquid
v	vapor

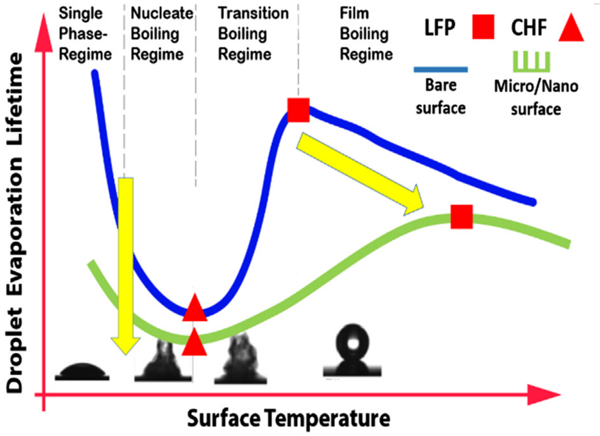

Fig. 1. Sessile droplet evaporation curve.

metals. A dramatic reduction of the atomization process compared to the bare surface, high cooling rate (higher in the case of water) and suppression of the Leidenfrost phenomenon were reported. Weickgenant et al. (2011) investigated the impact of water drop onto electrospun polymer nanofiber mats deposited over heated stainless steel foils [12]. The enhancement of heat removal was attributed to the prevention of the receding motion of the contact line and to drop imbibition in the nanofiber mats. Kim et al. (2013) investigated the dynamics of water droplet on superheated superhydrophilic zircaloy nanotubes [13]. Delayed cutback phenomenon and shift in Leidenfrost point (70 °C larger compared to the bare surface) were observed and attributed to the enhanced wettability and spreading induced by the nanostructures. An explosive behavior of the droplet in the transition boiling regime was also observed. Kim et al. (2014) observed the dynamics of water droplets on micro and nanostructured zirconium alloy surfaces with high-speed visualization [14]. A higher Leidefrost point (70 °C and 40 °C shifts for nano and microstructures respectively compared with the bare surface), vigorous droplet rebounding dynamics, and higher stable hovering points were attributed to the enhanced wettability characteristic of the processed surfaces and the increased amount of micro nucleation sites that caused explosive nucleation and triggered liquid–vapor interface collapse of the droplet. Nair et al. (2014) investigated the effect of FC-72 droplets on carbon nanofibers surfaces with different heights [15]. In particular, the tallest carbon nanofiber surface (7.5 μm) yielded the highest Leidenfrost point (shift of 240 °C compared to the bare surface). Recently, Tong et al. (2017) investigated the behavior of water droplet on heated oxide titanium nanotubes [16]. An interesting phenomenon was observed, that is the lift-off of the liquid film from the substrate considered responsible of the delay of the Leidenfrost phenomenon. Contrary to the Ti bare surface, vapor film boiling was not observed on the nanotubes at 480 °C (limit of the experimental setup).

Among the nanostructures, Si Nanowires (NWs) can become a potential candidate due to the combination of their properties such as high-aspect ratio and low-thermal conductivity, that can be important for extending the transition superheat [8]. Indeed, Hochbaum et al. (2008) showed that wafer-scale arrays of rough Si nanowires with diameter in the range between 20 and 300 nm can reduce drastically the thermal conductivity to ~1.6 W/m/K (around 100-fold lower than the bulk Si) [17]. A simple, inexpensive and scalable approach to develop high-aspect ratio Si nanowire arrays is to employ the Metal Assisted Chemical Etching (MaCE) [18]. Random Si Nanowires have already shown an excellent performance in pool boiling [19] and flow boiling [20]