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An experimental investigation of single droplet impact cooling on hot enhanced surfaces fabricated by selective laser melting

X.W. Wang, J.Y. Ho, K.C. Leong *

Singapore Centre for 3D Printing, School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Republic of Singapore

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ABSTRACT

Water droplets on eight different enhanced surfaces were experimentally investigated to determine the droplet impact behaviors and their effects on the cooling performances of these enhanced surfaces. The surfaces were fabricated using selective laser melting (SLM), which is an Additive Manufacturing (AM) technique that uses a high power-density laser to melt and fuse metallic powders together. In the experiments, the surface material is an aluminum alloy (AlSi10Mg) and the liquid is water. The droplet diameter was maintained at 2.4 mm, impact Weber numbers of 28, 122 and 202 were used and the droplet frequencies ranged from 0.79 Hz to 3.97 Hz. These surfaces, which were heated above the Leidenfrost temperature, were investigated at incidence angles of 90° and 45° and their results were compared against a smooth surface. Using high speed imaging, the evolutions of droplet dynamics on the heated surfaces were determined and the effects of the droplets' behavior on the cooling performances of the enhanced surfaces were elucidated. Our results showed that fin density played an important role in the droplet dynamics. When the fin density was high, the integrity of the droplet can be maintained after impact. On the other hand, increasing the fin height can usually improve the droplet heat transfer on clavate fin surface. For the Low density and the Globe surfaces (cylindrical + clavate), the droplets could be trapped on the fin surfaces which enhanced cooling. A combination of film boiling and nucleate boiling was observed on the Low density, the Clavate fins and the Globe fin surfaces. From transient cooling curves obtained for the various surfaces, it was determined that the Globe, High clavate and Low density surfaces demonstrated significantly better cooling performances as compared to the other enhanced and smooth surfaces. The best cooling performance was achieved with the Globe surface at $We = 121$, $f = 3.97$ and $\theta = 90°$.

1. Introduction

Present research in film boiling can be broadly classified into single droplet impact on a hot surface, quenching and spray cooling. For single droplet cooling, Bernardin et al. [1] used a high speed photographic technique to investigate the impingement of water droplets on a polished surface and mapped the impact and heat transfer regimes for different droplet Weber numbers. They found that the temperatures corresponding to the critical heat flux and the Leidenfrost point showed little sensitivity to both droplet velocity and impact frequency. Kim et al. [2] determined that nanoporosity was crucial to increasing the Leidenfrost point during single drop impact. Bertola [3] studied the bouncing of Leidenfrost droplets using Newtonian and viscoelastic liquids. The equilibrium diameters of the droplets were between 2.66 mm and 3.49 mm. The test specimen was made of aluminum, the surface temperature was maintained at 400 °C and the Weber numbers were between 7 and 160. He found that the viscoelasticity of the droplets hardly changed the spreading diameter but reduced the retraction velocity and suppressed the droplet rebound. Bertola [4] subsequently investigated millimetric water droplets impacting on a surface. The surface temperatures were between 50 °C and 400 °C and droplet Weber numbers up to 160 were tested. He defined five impact regimes, which are (1) rebound with secondary atomization, (2) splashing with secondary atomization, (3) secondary atomization, (4) rebound and (5) splashing. The impact regimes were plotted on a quantitative two-dimensional map.

Yu et al. [5] used a multi-scale numerical simulation model to investigate the impact of a water droplet on a hot solid surface in the Leidenfrost regime using the finite volume method. The droplet shape, impact parameters and contact time were obtained and their results were agreeable with the experimental data obtained. Burton et al. [6] used laser-light interference and high speed

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* Corresponding author.
E-mail address: mkcleong@ntu.edu.sg (K.C. Leong).

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Nomenclature

A	area (m$^{2)}$
c	specific heat (J/kg K)
d	drop diameter (mm)
f	droplet frequency (Hz)
h	heat transfer coefficient (W/m^2 K)
H	latent heat of vaporization (J/kg)
$\dot{Q}$	heat rate (W)
v	velocity (m/s)
V	volume (m^3)
We	Weber number
T	temperature (°C)
t	time (s)

Greek symbols

σ	surface tension (N/m)
ρ	liquid density (kg/m^3)
θ	angle of impact (°)

Subscripts

s	solid
w	wall
f	fluid
nb	boiling
nc	natural convection
rad	radiation

imaging to measure the radius and curvature of the liquid droplets, the height of the vapor pocket and non-axisymmetric fluctuations of the interface. They found that the geometry of the vapor pocket depended mainly on the drop size but not the substrate temperature. Yao and Cai [7] used a monosize droplet stream and a rotating disk to study the water droplets impacting at small angles on the hot surfaces. They found that the existence of a tangential relative velocity tended to destabilize the droplet at small angles of impact. The tangential relative velocity can reduce the chance of physical contact between the droplet and the surface. Chen et al. [8] studied the collision of diesel oil droplets on an inclined hot stainless steel surface and determined that the residence time of the droplets on the hot surface was independent of the impinging angle and normal impinging velocity. Wachters and Westerling [9], on the other hand, studied the heat transfer for a water droplet impinging on a hot plate. They found that when the Weber numbers were small ($We < 30$), there were no droplet disintegration. With intermittent Weber numbers ($30 < We < 80$), the droplets did not disintegrate until they rebounded from the hot surface. However, for higher normal impact Weber numbers ($We > 80$), the droplets disintegrated during the initial part of the impact. Breitenbach et al. [10] developed a theoretical model for heat transfer of a single drop impacting onto a hot surface above Leidenfrost temperature. Their model considered the development of thermal boundary layers in the liquid and solid regions, liquid evaporation and the creation of an expanding vapor layer. It was also applicable to spray impact and heat transfer coefficient calculations. Their theoretical predictions were shown to be in good agreement with the experimental results obtained.

On the investigation on quenching, Yagov et al. [11] studied the cooling of nickel, stainless steel and copper spherical patterns at temperatures above 700 °C. Their results revealed that the temperature field lost its spherical symmetry and high temperature gradients were observed in the radial direction and along the surface. Vakarelski et al. [12] investigated the quenching of superhydrophilic, hydrophilic, hydrophobic and superhydrophobic spheres. Except for the superhydrophilic sphere, all the other surfaces were observed to be in the film boiling regime. It was demonstrated that the superhydrophilic surface not only increased the Leidenfrost temperature but also enhanced the boiling heat transfer. For the superhydrophobic surface, the heat transfer behavior deviated from the classical boiling curve whereas for the textured superhydrophobic surface, the heat flux increased smoothly with wall superheat. Shahriari et al. [13] used electrowetting fields to disrupt the vapor layer in order to promote liquid surface wetting on a surface at Leidenfrost temperature. Because the transient convection replaced the heat conduction across the vapor gap, an order of magnitude increase in the heat transfer rate was obtained. The electric fields were observed to have altered the cooling curve and effectively suppressed film boiling by vapor instability control. Paul et al. [14] studied the emergence, growth, and eruption of vapor domes in a liquid puddle above the Leidenfrost temperature. A theoretical model to predict the formation of vapor domes and its subsequent instability was proposed.

Using acetone, isopropanol and R134a as the working fluids, Ok et al. [15] studied the Leidenfrost droplet motion on surfaces with topological ratchets of periods ranging from 800 nm to 1.5 mm. Their results indicated that for the 800 nm ratchets, the low boiling points fluids showed no unidirectional motion. However, for acetone and isopropanol, unidirectional droplet motion was still observed on micron and millimeter scale ratchets for surface temperatures up to 360 °C and 230 °C, respectively. Linke et al. [16] developed asymmetric teeth to achieve the self-propelled Leidenfrost droplets whereas Dupeux et al. [17] used a crenelated surface to increase the friction of the Leidenfrost droplets. Feng et al. [18], on the other hand, utilized magnetron sputtering and hybrid ion beams deposition to fabricate a ratchet thin film for self-propelled Leidenfrost droplet. It was determined that the surface with higher hydrophobicity exhibited a higher Leidenfrost point.

For spray cooling, Chabičovský et al. [19] investigated the influence of the oxide layer on the Leidenfrost temperature using both numerical and experimental approaches. They found that the oxide layer serves as an insulation, increased the cooling intensity for water spray cooling and shifted the Leidenfrost temperature. Zhang et al. [20] used deionized water to investigate the heat transfer effects of spray characteristics on flat and enhanced surfaces. It was determined that the heat transfer was effectively improved by the enhanced surfaces compared with a flat surface with single and two phase region flows. The flow rate and orifice-to-surface distance for spray cooling on both flat and enhanced surfaces were found to have influenced the spray cooling results. Wang et al. [21] studied spray cooling with liquid ammonia. The cooling surfaces included three different surfaces, which were surface-treated by electrochemistry at different levels, surfaces coated by micro copper particles in different sizes and surfaces combining microporous coating with macro channels. They pointed out that the final surface possessed the best heat removal capacity and the spray cooling performance was enhanced by larger specific surface area and higher boiling sites density. de Souza and Barbosa [22] investigated the spray cooling characteristics of plain and copper foam enhanced surfaces with R-134a. They found that the heat transfer coefficient for copper foam based on the external surface was significantly lower than that for the plain surface. They postulated that a combination of factors associated with a decrease of film velocity and an increase in film thickness could have reduced the overall surface efficiency in the foam structure.