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

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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 $\theta = 90^\circ$.

Keywords:

Leidenfrost point; Film boiling; Single droplet; Droplet trapping; Selective laser melting; Clavate fin

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

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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.

Nomenclature

A	area (m ²)	<i>Greek symbols</i>
c	specific heat (J/kg·K)	σ surface tension (N/m)
d	drop diameter (mm)	ρ liquid density (kg/m ³)
f	droplet frequency	θ angle of impact (°)
h	heat transfer coefficient (W/m ² ·K)	
H	latent heat of vaporization (J/kg)	
$\dot{Q}$	heat rate (W)	<i>Subscripts</i>
v	velocity (m/s)	s solid
V	volume (m ³)	w wall
We	Weber number	f fluid
T	temperature (°C)	nb boiling
t	time (s)	nc natural convection
		rad radiation

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 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. de Souza and Barbosa [23] also evaluated the heat transfer coefficient in spray cooling for three different copper surfaces with R-134a. They found that the heat transfer rate on the copper foam surface was much larger than that on the groove and plain

surfaces. However, the surface type did not influence the critical heat flux (CHF) significantly. Zhang et al. [24] experimentally investigated the spray cooling characteristics for flat surface, straight fin surface and porous tunnel surface with water. The results showed that the porous tunnel surface has the best performance in all tests under the same acceleration condition of the heater surfaces. The spray cooling capability for the straight fin surface was found to be better than that of the flat surface for low flow rate and low nozzle height spray cooling conditions. Silk et al. [25] conducted an experimental research on the impact of structured surface geometry and spray axis inclination for spray cooling. The surfaces consisted of a flat surface, cubic pin-fin surface, pyramid surface and straight fin surface. The results showed that the straight fin surface had the largest heat flux enhancement and a maximum heat flux enhancement of 75% at an inclination angle of 30° relative to the flat surface in the normal position. Wang et al. [26] used R404A to examine the heat transfer characteristics during spray cooling with a straight tube nozzle. Their results indicated that the spray cooling heat transfer was temporally and spatially non-uniform and there was a 2-mm radial sub-region around the spray center with a high transient heat flux. The heat fluxes for spray cooling on four different surfaces, such as smooth surface, drilling surface, straight fin surface, and combined surface having both holes and fins had been researched by Wang et al. [27]. Their experimental results showed that the drilling surface had the highest heat transfer coefficient and the combined surface had the highest cooling efficiency. Zhang et al. [28] investigated the heat transfer characteristics of one smooth and 12 enhanced silicon surfaces with micro structures in deionized water. They found that the heat transfer was not significantly greater than the smooth surface in the flooded region, but much greater in the thin film and partial dryout regions. The microstructured surface with larger characteristic sizes had a smaller area enhancement factor whereas the surface with smaller characteristic sizes could not be easily wetted.

Based on the above brief review, it can be seen that most of the investigations on the cooling of surfaces were performed on nano/micro-sized structured surfaces produced by some surface coating method [2] or by conventional manufacturing techniques [20]. We take the coating method as an example. As the coating is not intrinsically part of the substrate surface, the thermal contact resistance between the coating and substrate surface will reduce the overall thermal performance of the specimen. In addition, the coating will also tend to degrade and peel over time. On the other hand, intrinsic surface structures produced by conventional manufacturing techniques often have limited geometrical variations and complexity. These drawbacks can be overcome by recent developments in selective laser melting (SLM) techniques. Selective laser melting is a branch of additive manufacturing which enables functional metallic components to be fabricated. In SLM, a layer of metallic powder material is first deposited onto a substrate. A laser then selectively scans a cross section predefined by the computer aided design (CAD) file which in turn melts and fuses the powder. A three-dimensional structure can be produced by melting consecutive layers of powder over each other and producing components that are more than 99% dense. This method allows complex three-dimensional structures to be produced without the need of molds and thereby reducing production lead time and manufacturing efficiency. Using SLM, structures of micro to millimeter length scales can be produced with good dimensional accuracy for single-phase [29] and nucleate pool boiling [30] heat transfer applications and substantial heat transfer enhancements were reported. With appropriate design, these structures can also be used to enhance cooling in the film boiling regime and can be easily employed for industrial use.

In view of the above reasons, the present work aims to investigate the effects of micro/millimeter-sized structured surfaces on the droplet dynamics and cooling performance using water as the cooling medium. Eight enhanced surfaces with pin fin arrays of different fin geometries and arrangements

were fabricated by SLM and their transient boiling curves between the temperature range of 150°C and 400°C were characterized. In addition to cylindrical and cone shaped fins, novel fins with clavate shapes were also produced and investigated with the aim of increasing the droplet residence time to enhance cooling. In addition, the effects of parameters such as Weber number, droplet frequency and droplet incidence angle on the transient boiling curves were also investigated. Using high speed visualization, the evolutions of the droplets on the heated surfaces were determined and the effects of the droplet behavior on the cooling performances of the enhanced surfaces were elucidated. To the best of the authors' knowledge, investigation on the droplet impact cooling of enhanced structures produced by SLM such as the Cone and clavate structures that are presented in this paper has not been previously reported. The metallic structure, with better mechanical properties and higher thermal conductivity, can withstand the phase change heat transfer process for a longer time. The present investigation seeks to identify a promising structure for higher surface temperature cooling typically encountered in quenching applications, fire suppression systems and nuclear power plants.

2. Experimental setup and procedures

In this study, a free falling drop method was adopted to study the collision process and heat transfer characteristics of droplets impinging onto the heated surfaces above the Leidenfrost temperature. The experimental setup employed in the present investigation which is similar to those of Refs. [3, 4] is depicted in Fig. 1. The setup consists of four parts: (1) image acquisition system, (2) droplet generation system, (3) heater assembly and (4) data acquisition system. The image acquisition system, which consists of a FASTCAM 1024 PCI high speed camera and an illumination system, was used to observe and record the collision behavior of the droplets on the smooth and enhanced surfaces. In order to capture the evolution of droplets during the collision process, a high speed camera frame rate of 2000 fps was selected. On the other hand, the droplet generation system consists of a syringe with needle gauge, a syringe pump and a positioner. The needle gauge was used to maintain the droplet diameter (d) of 2.4 mm during the experiments and the droplet frequency (f) was varied using a syringe pump. The droplets were generated by a syringe pump at three different velocities. At each velocity, the volume of water for 200 water droplets was determined from the gauge of the syringe. With the volume of water recorded and by further assuming that the droplets are spherical, the diameter of the droplet was determined to be $2.4 \text{ mm} \pm 0.06 \text{ mm}$ over the range of drop frequencies tested. The computed droplet diameter was subsequently verified against the measurements taken from a high speed camera. In addition, the vertical distance between the specimen surface and the needle gage can also be adjusted using the positioner so as to vary the droplet's impinging velocity (v).

Details of the heater assembly are shown in Fig. 2. It consists of a copper block and three cartridge heaters fitted into the base of the copper block. Each of the cartridge heaters has a maximum power dissipation of 225 W and all three cartridge heaters were connected to a transformer which allowed the input power to the cartridge heaters to be varied. The test specimen was adhered to the top surface of the copper block using a thermally conductive paste. Each test specimen has a 1-mm blind-hole located at 2.5 mm below its top surface. A K-type thermocouple was installed in the hole to obtain the surface temperature of the specimen (T_w). In addition, three K-type thermocouples (at 6 mm apart) were also embedded into the blind-holes located along the copper block to further verify the accuracy of specimen surface temperature. The thermocouple readings were recorded using the Yokogawa MX100 data acquisition unit at the sampling rate of 1 Hz. Throughout the experiments, the copper block was insulated on all sides to prevent excessive heat loss. All tests were conducted with de-ionized water, the water temperature was maintained at 25°C and the accuracy of the thermocouples is within $\pm 1.1^\circ\text{C}$.

The main aim of this study is to investigate the effects of surface structure, droplet impinging velocity (v), droplet frequency (f) and droplet incidence angle (θ) under the film boiling regime. Using the values of v , d and the fluid properties, the Weber number We which accounts for the droplet impinging velocity can be obtained from Eq. (1). On the other hand, f can be varied using the syringe pump whereas the variation in θ can be achieved by orienting the heater assembly. It should be noted that $\theta = 90^\circ$ is defined as the angle between the horizontal surface and the direction of gravitational acceleration, as shown in Fig. 1. All the parameters used in the experiments are summarized in Table 1.

$$We = \frac{\rho v^2 d}{\sigma} \quad (1)$$

The experiment was conducted by first heating the specimen surface to a temperature (T_w) of 400°C , which is higher than the Leidenfrost temperature of a smooth surface. Thereafter, the power to the cartridge heaters was switched off. At the same time, the syringe pump was activated and the temperature of the specimen (T_w) was simultaneously recorded. The experiment was terminated when T_w decreased to approximately 150°C . In order to observe and record the droplet evolution above the Leidenfrost point, after the temperature recordings were completed, the temperature of the surfaces was increased to 500°C and the high speed camera was used to capture the droplet impact process.

Fig. 1 Schematic of experimental setup

Fig. 2 Heater assembly and test specimen

Table 1 Experimental parameters.

Experimental parameters	Values
Drop diameter (d)	2.4 mm
Density of water (ρ)	1000 kg/m ³
Impinging velocity (v)	0.9 m/s, 1.9 m/s, 2.5 m/s
Droplet temperature (T)	25°C
Incident angle with horizontal surface (θ)	45°, 90°
Surface tension of water (σ)	72 mN/m
Weber number (We)	28, 122, 202
Droplet frequency (f)	0.79 Hz, 2.38 Hz, 3.97 Hz

3. Fabrication and characterization of test specimens

The test specimens with enhanced structures employed in the present investigation were fabricated using the selective laser melting facility (SLM Solutions GmbH) in the Singapore Centre for 3D Printing of Nanyang Technological University, Singapore. An aluminum alloy (AlSi10Mg) of 20 μm to 63 μm size distribution was used as the base powder. A Gaussian distributed Yb:YAG laser with a maximum power of 400 W and a laser beam spot size of 80 μm was utilized to melt and fuse the powder layer-by-layer based on the input of a Computer Aided Design (CAD) model. In the present investigation, a laser power of 350 W, scanning speed of 1150 mm/s and hatching spacing of 0.17 mm were selected. Ten test specimens with arrays of pin fin structures of different fin geometries and arrangements are fabricated. For each surface, the pin fins were fabricated onto a 25 mm $\times$ 25 mm $\times$ 5 mm base plate as an integrated build piece.

The CAD drawings of five enhanced surfaces are shown in Fig. 3 and their physical parameters are summarized in Table 2. The High density, Medium density and Low density surfaces which correspond to Fig. 3 (a), (b) and (c), respectively consist of arrays of cylindrical pin fins of different fin pitches and fin heights but the same fin diameter. On the other hand, the Cone surfaces consist of array of conical fins with a height of 1280 μm and a base diameter of 1160 μm . The fin pitch of the Cone fin is similar to that of the Low density fin. Unlike the conical fins which reduce in diameter with increasing height, the Low clavate, Medium clavate, High clavate and Globe surfaces consists of club-shaped fins such that the diameter near the apex is larger than the base diameter. A comparison of the Medium clavate and Globe fins is shown in Fig. 3 (f) and a comparison of the Low, Medium and High clavate fins is shown in Fig. 3 (g). Both the Medium clavate and Globe fins have the same height and consist of a vertical stem and a spherical tip. The stem diameter of the Globe fins is smaller than those of the Clavate fins and has geometry similar to a cylinder. In addition, the Globe fin has a convex fin tip which is larger than that of a clavate geometry and therefore, the term ‘Globe’ is used. The Low, Medium and High clavate fins have the same base diameter but have the heights of 1280 μm , 2560 μm and 3840 μm , respectively. Microscope images of some fabricated enhanced surfaces are depicted in Fig 4. Due to the laser melting process, these surfaces were observed to be significantly rougher. Nevertheless, it can be seen that the bulk geometries of the fabricated fins are similar to the CAD design.

Finally, a smooth surface made of commercial Al-6061, which served as a control surface for comparison against the enhanced surface, was also fabricated.

Fig. 3 Top and side views of test specimens with (a) High density, (b) Medium density and (c) Low density, (d) Cone, (e) Globe surfaces, (f) comparison of Medium clavate and Globe fins and (g) comparison of a Low, Medium and High clavate fins.

Fig. 4 Microscopic images of (a) High density, (b) Low density, (c) Cone, (d) Low clavate, (e) High clavate and (f) Globe surfaces.

Table 2 Surface dimensional characteristics in this study.

Specimen name	Fin diameter (μm)	Fin height (μm)	Fin pitch (μm)	Fin shape
High density	300	600	400	Cylindrical fins
Medium density	300	600	600	Cylindrical fins
Low density	300	1280	1250	Cylindrical fins
Cone	1160	1280	1250	Conical fins
High clavate	600-1260	3840	1250	Clavate fins
Medium clavate	600-1260	2560	1250	Clavate fins
Low clavate	600-1260	1280	1250	Clavate fins
Globe	420-1110	2570	1670	Cylindrical +clavate fins
Smooth	-	-	-	-

4. Results and discussion

4.1 Droplet impact processes

When a surface is heated above the Leidenfrost temperature, the portion of the falling water droplet near the hot surface quickly evaporates and results in a hydrodynamic unstable state where a vapor layer forms between the hot surface and the droplet. As the vapor layer inhibits the surrounding liquid to further cool the surface, heat transfer from the surface above the Leidenfrost temperature is significantly lower than that in the nucleate boiling regime. In droplet impact cooling above the Leidenfrost temperature, the evolution of droplet dynamics on the heated surface has a predominant effect on the surface heat transfer characteristics. The evolution of droplet typically observed during the impact cooling process consists of (1) droplet release, (2) droplet coming into contact with hot surface, (3) droplet spreading due to inertia, (4) droplet retraction due to surface tension and (5) droplet rebound from surface. Heat is transferred from the instance when the droplet comes into contact with the hot surface until it rebounds from the surface. Therefore, heat transfer above the Leidenfrost temperature can be improved by preventing droplet rebound or by increasing the hovering time of the droplet on the surface.

Figures 5 – 10 show the images of the droplet impact process for five enhanced structures and a smooth surface at different We values and with T_w , f and θ maintained at 500°C, 2.38 Hz and 90°, respectively. According to Rayleigh [31] and Chen et al. [8], the residence time of the drop on the hot surface can be predicted as 10.9 ms and 15.5 ms, respectively and they are expressed as

$$tr = \frac{\pi}{4} \sqrt{\frac{\rho d^3}{\sigma}} \quad (2)$$

$$tr = 1.12 \sqrt{\frac{\rho d^3}{\sigma}} \quad (3)$$

From the images recorded, it can be observed that the droplet residence time was about 12 ms, which is in a good agreement with Rayleigh's theory.

For the High and Medium density surfaces, as shown in Figs. 5 and 6, it can be seen that at low We , the droplet spreads upon impact onto the surface, retracts and subsequently rebounds from the surface without breaking up. In addition, with the increase in We , the maximum droplet spread diameter and rebound height also increase. Among all the surfaces, the High density surface resulted in the smallest maximum spread diameter and droplet's integrity was preserved during the impact. As the High density surface consists of very densely populated fins, air trapped between the fins prevented the droplet from penetrating into the fin base and the droplet spreading process only occurred near the fin tip. In addition, the fins also serve as obstacles which impede the lateral spreading of the droplet, and hence, limit the spread diameter of the droplet. Due to these reasons, the contact area and time between the droplet and High density and Medium density surfaces decreased significantly compared with other enhanced and smooth surfaces. However, it should be noted that unlike the High density surface, for the Medium density surface, disintegration of droplet under with large Weber number was observed. The disintegrated smaller droplets subsequently flow into the small channels in between the fins.

Figure 10 shows the impact process of a droplet on a smooth surface. Unlike the High and Medium density surfaces, at $We = 28$, it can be seen that droplet does not retract but spread and broke off into multiple smaller droplets. After the droplet had broken off, most of the smaller droplets rebounded off the surface, leaving a small portion hovering over the surface (refer to Appendix A - supplementary video 1). Due to the larger contact area between the droplet and the surface, heat transfer from the smooth surface is expected to be higher than the High and Medium density surfaces. On the other hand, Fig. 7 depicts the droplet dynamics on the Low density surface during the impact process. Due to the large fin spacing, the structure enabled the droplet to penetrate and spread into the fin base. After the spreading process, the droplets were seen breaking off into multiple smaller droplets. However, as this breaking off process occurred near the fin base, the presence of the fins served as barriers which not only prevented the smaller droplets from rebounding off the surface but, at the same time, resulted in the coalescence of neighboring droplets (refer to Appendix A - supplementary video 2). Among all the surfaces, the Globe surface demonstrated the highest droplet contact time and lowest rebound velocity. As shown in Fig. 9, the spacing between the Globe fins is sufficiently large to allow the droplet to penetrate to the fin base. Upon impact, the breaking up of the droplet was observed. However, as the fin tip is large, it prevented the smaller droplets from escaping the fin base and thereby trapping the droplets between the fins (refer to Appendix A - supplementary video 4). With a large number of droplets being contained on the surface, there are significantly high droplet surface contact time and additional fin area for heat transfer. These results suggest that the Globe surface is a promising structure for droplet impact cooling.

Finally, it should be noted that for all the surfaces, there exists a critical Weber number above which the surface tension will not be able to recover the shape of the droplet after impact and the droplet will break into smaller droplets. Due to the difference in fin geometry and arrangement, the critical Weber number differs for each surface. For instance, for the High and Medium density surfaces, droplet breakoff was recorded at $We = 122$ whereas for the smooth surface, this phenomenon was observed at $We = 22$. The maximum spreading diameter and disintegration of droplet on different surfaces obtained in the present investigation and a comparison against the surfaces reported by other researchers are summarized in Table 3.

Table 3 Maximum spreading diameter in past works and present experimental results.

Authors or surface structure	Correlations	Maximum spreading diameter at different We		
		We = 28	We = 122	We = 202
Ueda et al. [32]	$0.87(\frac{We}{6} + 2)^3 d$	0.0054m	0.0099m	0.0125m
Akao and Araki [33]	$0.631We^{0.39}d$	0.0056m	0.0099m	0.0120m
Hatta et al. [34]	$(0.093We^{0.74} + 1)d$	0.0050m	0.0102m	0.0137m
High density		0.006m	0.0080m	0.0084m
Medium density		0.0058m	disintegration	disintegration
Low density		disintegration	disintegration	disintegration
Low cone		disintegration	disintegration	disintegration
Globe		disintegration	disintegration	disintegration
Smooth		disintegration	disintegration	disintegration

Fig. 5 Droplet impact processes on the High density surface at (a) $We = 28$, (b) $We = 122$ and (c) $We = 202$ with $T_w = 500^\circ\text{C}$, $f = 2.38 \text{ Hz}$ and $\theta = 90^\circ$.

Fig. 6 Droplet impact processes on the Medium density surface at (a) $We = 28$, (b) $We = 122$ and (c) $We = 202$ with $T_w = 500^\circ\text{C}$, $f = 2.38$ Hz and $\theta = 90^\circ$.

Fig. 7 Droplet impact processes on the Low density surface at (a) $We = 28$, (b) $We = 122$ and (c) $We = 202$ with $T_w = 500^\circ\text{C}$, $f = 2.38$ Hz and $\theta = 90^\circ$.

Fig. 8 Droplet impact processes on the Cone surface at (a) $We = 28$, (b) $We = 122$ and (c) $We = 202$ with $T_w = 500^\circ\text{C}$, $f = 2.38$ Hz and $\theta = 90^\circ$.

Fig. 9 Droplet impact processes on the Globe surface at (a) $We = 28$, (b) $We = 122$ and (c) $We = 202$ with $T_w = 500^\circ\text{C}$, $f = 2.38$ Hz and $\theta = 90^\circ$.

Fig. 10 Droplet impact processes on the Smooth surface at (a) $We = 28$, (b) $We = 122$ and (c) $We = 202$ with $T_w = 500^\circ\text{C}$, $f = 2.38$ Hz and $\theta = 90^\circ$.

In order to investigate the effects of θ on the droplet impact cooling performance, experiments were repeated at $\theta = 45^\circ$ and $We = 122$ on the better performing enhanced surfaces, viz., Low density, Cone and Globe surfaces and a comparison of their impact process is shown in Fig. 11. For the Cone surface, it can be seen that the spreading diameter of the droplet was significantly enlarged along the gravitational direction and most of droplets escaped the surface after the initial impact. On the other hand, for the Low density surface, the droplet break-off after the initial impact resulted in smaller droplets being produced. However, due to the presence of the fins which prevented the smaller droplets from escaping, these droplets initially remained on the surface but gradually rolled off the surface. For the Globe surface, similar droplet trapping as that observed at $\theta = 90^\circ$ was also recorded at $\theta = 45^\circ$, indicating that droplet incidence has negligible effect on the droplet dynamics.

Fig. 11 Droplet impact process on (a) Low density, (b) Cone and (c) Globe surfaces at $T_w = 500^\circ\text{C}$, $We = 122$, $f = 2.38$ Hz and $\theta = 45^\circ$.

4.2 Combination of film boiling and nucleate boiling over Leidenfrost temperature

Figure 12 shows the evolution of the droplet on the Low density surface, where $t = 0$ ms denotes the instant when the droplet comes into contact with the surface. As the diameter of the droplet was larger than the fin pitch and the surface temperature had reached a certain value, the droplet after impact was trapped by the tall cylindrical fins between the fin pitch. However, it can be seen that the base of the droplet was not in direct contact with the fin base but instead was levitated slightly above the fin base. Due to the intermolecular forces between the droplet and the fin surface, the droplet was also adhered onto the fin near the fin tip. With increasing time, the droplet oscillated in its position and gradually reduced in size due to the phase change process and eventually vaporized at $t = 650$ ms. The volume of droplet decreased with time because of heat transfer on the droplet surface and the heat transfer can be approximately assessed by Eqs. (4) and (5), where the heat transfer coefficient on the droplet surface is directly proportional to the rate of droplet decrease. In Fig. 12 (a), the trapped droplet is within the yellow circle and stable droplet within the red circle. The adhered droplet disappeared in 650 ms but the stable droplet's volume varied slightly. It can be deduced that the heat transfer coefficient for the adhered droplet is tens to hundreds of times larger than that of the stable film boiling (refer to Appendix A - supplementary video 4).

$$H_f \rho_f \frac{dV_f}{dt} = hA(T_w - T_f) \quad (4)$$

$$h \sim \frac{dV_f}{dt} \quad (5)$$

Once the droplet came into contact and was adhered onto the fin surface, it was trapped by the fin and the heat transfer from the fin can be classified into five different regions, with each region dominated by a different mechanism as summarized below and shown in Fig. 13.

Region I: This region is located near the fin base. As the temperature of the fin in this region is high, the film boiling regime dominates. A layer of vapor film was generated and the droplet was unable to cover the surface of the fin which resulted in droplet levitating above the fin base as shown in Fig. 13.

Region II: This region is located at the low portion of the fin. As the liquid-surface adhesion force causes the droplet to cling onto the fin, the fin surface temperature in this region is lower than that of Region I such that nucleate boiling regime could be initialized and sustained. The nucleate boiling regime is desired as it offers the highest heat transfer coefficients as compared to the single-phase convection and film boiling regimes. Since nucleate boiling heat transfer prevails in this region, it has the highest heat transfer rate among all regions.

Region III: Due to the high heat transfer rate in Region II, the temperature of the fin further reduces with increasing fin height. In Region III, the surface temperature of the fin was lower than nucleate boiling temperature and single-phase convective heat transfer dominates. However, adhesion effects are still present in this region as the droplet is still clinging onto the fin.

Region IV: With fin height increasing sufficiently, the temperature difference between the fin surface and the droplet disappeared. The temperature of fin tip is maintained at the saturated temperature and no heat transfer took place.

It should be noted that the above phenomena can only take place when the fin tip is below a certain temperature. The fin can be cooled with the falling droplet during the falling process. Increasing the droplet frequency can result in rapid cooling of the fin surface. By observing the volume decreasing rate, it can be concluded that the heat transfer rate from Regions II is the most significant among all the regions.

The above boiling mechanisms and droplet adhesion were also observed on the Globe surface. In addition, due to the club-shaped fin of the Globe surface, the large fin tip suppressed the droplet towards the fin base and hence, maintained a large portion of the droplet near the fin base where Region II is located and significantly increased the heat transfer by nucleate boiling. As shown in Fig. 12 (b), the droplet phase change process took approximately 300 ms which was less than half the time taken by the Low density surface (refer to Appendix A - supplementary video 3).

Fig. 12 Trapping of droplet by (a) Low density surface at $T_w = 270^\circ\text{C}$, $We = 122$, $f = 2.38$ Hz and $\theta = 45^\circ$ and (b) Globe surface at $T_w = 283^\circ\text{C}$, $We = 122$, $f = 2.38$ Hz and $\theta = 45^\circ$.

Fig. 13 Illustration of heat transfer regime for a droplet on a tall cylindrical fin.

4.3 Effects of surface structures on transient cooling curve

For film boiling, as the heat transfer resistance on the liquid surface is much higher than the solid heat conduction resistance, the lumped method can be used to estimate the heat transfer performance for different surfaces. As shown in Eqs. (6) and (7), and assuming $\dot{Q}_{nc}$ and $\dot{Q}_{rad}$ to be negligible, the heat transfer coefficient (h) of a surface depends on the time rate of change of the solid temperature ($\frac{dT_w}{dt}$) and the solid thermophysical properties ρ_s , V_s , C_s which denotes solid density, volume and specific heat, respectively. By assuming a constant $(T_w - T_f)$ value, as the change in $(T_w - T_f)$ with time is small in the film boiling regime, h can be approximately assessed by the value of $\frac{dT_w}{dt}$. Therefore, surfaces with larger $\frac{dT_w}{dt}$ also denote higher cooling performances. This can be observed from Fig. 15 for surfaces with the Low density and Globe fins. Larger $\frac{dT_w}{dt}$ values also show better cooling performance and for a given surface, the maximum $\frac{dT_w}{dt}$ also corresponds to the Leidenfrost point. A typical transient cooling curve of a heated surface subjected to droplet impacting cooling is shown in Fig. 14. Due to the change in wall temperature over time, different boiling regimes and heat transfer rates can be observed. These boiling regimes are divided into film boiling, nucleate boiling and single-phase convection. In the film boiling regime, the surface is covered by a layer of continuous vapor film, causing an increase in thermal resistance between the surface and the surrounding fluid. As a result, heat transfer by film boiling is significantly low. With the reduction in the surface

temperature, transition from the film boiling to the nucleate boiling regime occurs. In this regime, vapor bubbles begin to form on the hot surface, grow in size and eventually depart from the nucleation sites. The formation and departure of these bubbles aid the removal of heat from the surface and enhance the heat transfer. As latent heat is involved in the heat transfer process, nucleate boiling has significantly larger heat transfer coefficient than the two other regimes. Finally, when the surface temperature is below the incipience temperature, single phase convection heat transfer prevails. As a result of the significant differences in their heat transfer rates, the film boiling regime, nucleate boiling regime and Leidenfrost point can be identified from the change in gradient of the transient cooling curve [1, 11]. Using the experimental procedures outlined in Section 2, the transient cooling curves of the smooth and enhanced surfaces under different We , f , and θ values were obtained and their boiling regimes and Leidenfrost points were identified and presented in this section.

$$-\rho_s c_s V_s \frac{dT_w}{dt} = \dot{Q} = \dot{Q}_{nb} + \dot{Q}_{nc} + \dot{Q}_{rad} \quad (6)$$

$$\dot{Q}_{nb} = h(T_w - T_f) \quad (7)$$

Figure 15 shows the transient cooling curves of the smooth and enhanced surfaces at the same f and θ values of 0.76 Hz and 90°, respectively but at different We numbers. It can be seen that the temperatures of the surfaces reduced with increasing time. At low droplet frequency, the Leidenfrost point still exists. However, the change in gradient of the cooling curves which denotes the transition from film boiling to nucleate is less obvious. This is because the heat transfer rate ($\dot{Q}$) from a surface by droplet boiling reduces with decreasing f . Using the transient heat conduction equation of Eqs. (6) and (7) and assuming that the ρ_s , c_s and V_s terms remain unchanged, it can be seen that a reduction in ($\dot{Q}$) also resulted in the reduction in the gradient of the cooling curve ($\frac{dT_w}{dt}$). In addition, it should also be noted that the overall heat transfer rate from the surface consists of heat transfer by boiling of the droplet ($\dot{Q}_{nb}$), natural convection ($\dot{Q}_{nc}$) and radiation ($\dot{Q}_{rad}$) as shown in Eq. (6). At high droplet frequency (f), as $\dot{Q}_{nb}$ is much larger than $\dot{Q}_{nc}$ and $\dot{Q}_{rad}$, the transition from film boiling to nucleate boiling is obvious. However, when f values are small, the Leidenfrost point is not as noticeable.

Finally, it can also be observed that below T_w of approximately 300°C, a faster cooling rate was achieved with the Low density and Globe surfaces as compared to the High density and Smooth surfaces and the difference in cooling rate also increased with increasing We . The better performance of the Low density and Globe surfaces agreed well with the droplet dynamics presented in Section 4.1 where these surfaces were capable of increasing the droplet contact time and area and hence, enhanced the cooling. The cooling time needed was more than several hundred seconds and was much longer than quenching and spray cooling. This is also due to the low droplet frequency and large solid volume used [1, 2, 35].

Fig. 14 Transient cooling curve

Fig. 15 Transient cooling curves of various surfaces at $f = 0.79$ Hz, $\theta = 90^\circ$ and (a) $We = 28$, (b) $We = 121$ and (c) $We = 202$.

(a)

(b)

(c)

Fig. 16 Transient cooling curves of various surfaces at $f = 2.38$ Hz, $\theta = 90^\circ$ and (a) $We = 28$, (b) $We = 121$ and (c) $We = 202$.

(a)

(b)

(c)

Fig. 17 Transient cooling curves of various surfaces at $f = 3.97$ Hz, $\theta = 90^\circ$ and (a) $We = 28$, (b) $We = 121$ and (c) $We = 202$.

With the increase in f values to 2.38 Hz and 3.97 Hz as shown in Figs. 16 and 17, respectively, the transition from film boiling to nucleate boiling regime becomes apparent. For instance, as shown in Fig. 17 (a), at $f = 3.97$ and $We = 28$, for Medium density and Cone surfaces, T_w initially reduces gradually with time. However, when the Leidenfrost point was achieved at $T_w \approx 260^\circ\text{C}$ and $t \approx 700$ s, the nucleate boiling regime sets in and T_w reduces significantly over a shorter period of time, resulting in the steep cooling curves. For the Smooth surface, the Leidenfrost point was achieved at $T_w \approx 200^\circ\text{C}$ and $t \approx 1400$ s whereas for the High density surface, significantly lower Leidenfrost temperature was recorded ($T_w \approx 175^\circ\text{C}$) and the phenomenon also occurred much later ($t \approx 1700$ s) [8]. For the Low density and Globe surfaces, no Leidenfrost point was observed for the range of f and We tested. In addition, significantly faster cooling was achieved with these two surfaces, achieving T_w of 175°C in less than 600 s. The experimental results with Low density and Globe surfaces agreed well with the explanation presented in Section 4.2 and in Fig. 12 where heat transfer from surface is through a combination of nucleate boiling and droplet oscillation caused by the adhesion of droplets on the fin structure and the large temperature gradient along the fin. For the same Weber number, the performance of each surface was seen to increase with increasing f . For instance, at $We = 28$, the Medium density fin required around 1800 s to reach 160°C at $f = 0.79$ Hz whereas it required only 1000 s and 800 s to reach the same temperature when f was increased to 2.38 Hz and 3.97 Hz, respectively. Among all the surfaces tested, the Globe surface exhibits the best cooling performance and the fast cooling rate for this surface was achieved at $We = 121$, $f = 3.97$ and $\theta = 90^\circ$. Finally, it should be noted that the trends of the cooling curves for High density, Medium density and Low density fins are similar to the results of Kwon et al. [36] who investigated fin pitches from $20\text{ }\mu\text{m}$ to $100\text{ }\mu\text{m}$.

4.3.1 Effects of fin geometry

A comparison of the experimental results of the Low density surface, Cone surface and Low clavate surface at $We = 121$ and $\theta = 90^\circ$ at the frequencies (f) of 2.38 Hz and 3.97 Hz are shown in Fig. 18 (a) and (b) and a comparison of these fin geometries is depicted in Fig. 19. Since these three surfaces have the same fin pitch and fin height, their cooling performances are only affected by the fin geometry. From Fig. 18, it can be seen that the Low density surface has significantly better cooling performances as compared to the Cone and Low clavate surfaces. In addition, the Cone surface also has a better cooling performance than the Low clavate surface. This phenomenon can be explained

using the fin efficiency concept. The efficiency of the fin (η_{fin}) depends on the fin geometry and the dimensionless fin profile (ξ). This relationship is presented in Ref. [37]. Due to the different fin geometry, it can be deduced from Ref. [37] that the Cone fin has larger fin efficiency as compared to the Low density fin. This implies that the temperature at the tip of the Cone fin is significantly larger than that of the Low density fin. Therefore, the Leidenfrost phenomenon is still prevalent at the tip of the Cone fin and the water droplet will not be able to remain on the fin surface upon impact. On the other hand, as the temperature of Low density fin tip is lower, the recoil force on the water droplet is less significant and thereby allows the droplet to adhere onto the fin and enhance the surface's cooling performance. Based on the above explanation, the poorer cooling performance of the Low clavate surface could also be due to the higher fin efficiency which resulted in a higher fin tip temperature which prevented the droplet to be adhered onto the fin surface for enhanced cooling.

Fig. 18 Comparison of the Low density, Cone and Low clavate surfaces at $We = 121$ and $\theta = 90^\circ$ at (a) $f = 2.38$ Hz and (b) $f = 3.97$ Hz.

Fig. 19 Drawings of Low density, Cone and Low clavate fins.

The experimental results of the Medium clavate and Globe surfaces at $We = 121$ and $\theta = 90^\circ$ at the frequencies (f) of 2.38 Hz and 3.97 Hz are shown in Fig. 20 and a comparison of their fin structure is depicted in Fig. 3 (f). Since these two surfaces also have similar fin pitch and fin height, the surface cooling performances are affected only by the fin geometry. From Fig. 20, it is observed that the Globe surface exhibits better heat transfer performance as compared to the Medium clavate. As the spherical tip of the Globe fin is significantly larger than that of the Medium clavate fin, once a water droplet enters the gaps between the fins, the large spherical tip of the Globe fin prevents the water droplet from escaping the surface. This increases the droplet residence time and enhanced the cooling performances of the surface. An illustration on the entrapment of a water droplet by the Globe fins is shown in Fig. 21.

Fig. 20 Comparison of transient cooling curves of Medium clavate and Globe surfaces at $We = 121$ and $\theta = 90^\circ$ at (a) $f = 2.38$ Hz and (b) $f = 3.97$ Hz.

Fig. 21 Trapping of a water droplet by the Globe fins.

In summary, the Low density and the Globe surfaces are the two better performing surfaces in the present investigation. Based on the above analysis, it can be further concluded that the improved cooling performances of these two surfaces are influenced by different mechanisms. For the Low density surface, the lower fin efficiency as compared to other fin geometries resulted in lower fin tip temperature and enabled the water droplet to be attached to the fin tip. On the other hand, the Globe surface's large spherical tip prevents droplets which entered the fin base from escaping, increases the droplet residence time and enhances the boiling heat transfer.

4.3.2 Effects of fin height

The effects of fin height were also investigated. Figure 22 shows a comparison of the transient cooling curves of the Low, Medium and High clavate surfaces and the geometry of these fins are depicted in Fig. 3(g). These clavate surfaces have the same fin base diameter of $1260 \mu\text{m}$ and the same fin pitch of $1250 \mu\text{m}$ but have different fin heights. As the geometries and fin pitch of these surfaces are similar, the surfaces' heat transfer performance only depends on the fin height. From Fig. 23 it can be observed that the heat transfer performance of the surfaces increases with increasing fin height. This is because as the fin height increases, the temperature of the fin tip reduces. As the water droplet approaches the fin tip, the lower fin tip temperature reduces the recoil force on the droplet and allows longer droplet residence time on the fin tip.

Fig. 22 Comparison of transient cooling curves of Low, Medium and High clavate surfaces at $We = 121$ and $\theta = 90^\circ$ at (a) $f = 2.38$ Hz and (b) $f = 3.97$ Hz.

4.3.3 Effects of incidence angle and Weber number

The effects of droplet incidence angle were also examined and Fig. 23 shows the transient cooling curves of all the surfaces at $\theta = 45^\circ$ and with f and We at 3.97 Hz and 122, respectively. Similar to the results obtained for $\theta = 90^\circ$, Leidenfrost temperature was observed for the Medium density and Cone surfaces at $T_w \approx 250^\circ\text{C}$ and at $T_w \approx 200^\circ\text{C}$ for Smooth and High density surfaces. The cooling performances of Low density and High clavate surfaces are similar. However, it is interesting to note that the differences in the transient cooling curves between the Globe, Low density surfaces and High clavate are more significant at $\theta = 45^\circ$ than at $\theta = 90^\circ$ with the Globe surface demonstrating better cooling performances. The heat transfer performance for the High clavate surface is also slightly better than that of Low density fins and this is because the large spherical tip of the High clavate and Globe fins can prevent the droplets from escaping from the finned region. As shown in the high speed images in Fig. 12, at $\theta = 45^\circ$ and after droplet impact, the droplets tend to roll off the Low density surface whereas for the Globe surface, the club-shaped fins were able to trap the droplets within the fin spacing, preventing the droplets from rolling off and increasing the droplet-surface contact time.

Finally, a comparison to the Globe surface cooling curves at different f values, $We = 28$ and $\theta = 90^\circ$ is presented in Fig. 24 (a) and a comparison of the surface cooling curves at different We numbers, $f = 3.97$ Hz and $\theta = 90^\circ$ is shown in Fig. 24 (b). From Fig. 24 (a), it was determined that increasing f significantly improved the cooling performance of the Globe surface as indicated by the leftward shift of the transient cooling curve. As shown in Fig. 12, the droplet impact and phase change process on the Globe surface took approximately 302.5 ms. After the droplet was completely vaporized, there exists a waiting period before the next droplet was impinged onto the surface. Therefore, by increasing the drop frequency, the waiting period was reduced which in turn reduced the average temperature of the surface. On the other hand, as depicted in Fig. 24 (b), the increase in We has a less significant effect on the cooling performance of the Globe surface. Similar transient cooling curves were obtained at $We = 28$ and $We = 201$, whereas slightly improved cooling performance was achieved with $We = 122$. As We is related to the droplet impinging velocity (v), this comparison shows that the Globe structure is capable of trapping the droplet even at large v .

Fig. 23 Transient cooling curves of various surfaces at $We = 122$, $f = 3.97$ and $\theta = 45^\circ$.

Fig. 24 Comparison of transient cooling curves of Globe surface (a) at various f values with $We = 28$ and $\theta = 90^\circ$ and (b) at various Weber numbers with $f = 3.97$ and $\theta = 90^\circ$.

5. Conclusions

Single droplet impact and cooling experiments were performed using water on nine different surfaces (High density fin surface, Medium density fin surface, Low density fin surface, Cone fin surface, Low clavate fin surface, Medium clavate fin surface, High clavate fin surface, Globe and Smooth surface). The experiments were conducted by heating the surfaces above the Leidenfrost temperature. Weber numbers of 28, 122 and 201 and f values of 0.79, 2.38 and 3.97 were used.

From the high speed images obtained, it can be concluded that the High density surface allowed the integrity of the droplet to be maintained without breaking off after impact. The Low density and Globe surfaces, on the other hand, enabled the droplets to be trapped within the spaces between the fins and the droplets can be maintained on the surface even when θ was reduced to 45° . A combination of film boiling and nucleate boiling was found on the fins of the Low density and Globe surfaces. Due to the combination of film and nucleate boiling phenomena and trapping of droplets, these two surfaces demonstrated significantly better cooling performances as compared to other surfaces.

Based on the transient boiling curves obtained, it was determined that cooling performances of the surfaces agreed well with the droplet dynamics observed from the high speed images. The transition

from film to nucleate boiling regime was not observed for the Low density, High clavate and Globe surfaces suggesting that the presence of Globe film and nucleate boiling. On the other hand, the Medium density, Medium clavate, Low clavate and Cone surfaces were observed to increase the Leidenfrost temperature with the High density surface exhibiting lower Leidenfrost temperature than the Smooth surface. Furthermore, the surface cooling performances were shown to improve with increasing f values but were relatively less sensitive to the change in We . In all, the best cooling performance was achieved with the Globe surface at $We = 121$, $f = 3.97$ and $\theta = 90^\circ$.

The Leidenfrost phenomenon is observed in many high heat flux engineering devices such as in electronic circuits and nuclear reactor cores. However, this phenomenon is undesirable as it may result in overheating and damage of essential components, which compromises operation safety. Through adequate spatial control, droplet impact cooling is a viable thermal management solution which can also be employed to maintain uniform component temperatures under concentrated heat loads. From the results of the present investigation, it is hoped that these enhanced structures can be employed to provide better cooling for high heat flux components.

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Appendix A

Supplementary videos 1 - 4 associated with this article can be found in the online version <https://doi.org/10.1016/j.ijheatmasstransfer.2017.12.033>.

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