Unique lift-off of droplet impact on high temperature nanotube surfaces

Qiu, Lu; Jin, Jian; Sun, Lidong; Duan, Fei; Tong, Wei

2017

Tong, W., Qiu, L., Jin, J., Sun, L., & Duan, F. (2017). Unique lift-off of droplet impact on high temperature nanotube surfaces. *Applied Physics Letters*, 111(9), 091605-.

<https://hdl.handle.net/10356/86879>

<https://doi.org/10.1063/1.4994022>

© 2017 The Authors (Published by AIP Publishing). This paper was published in *Applied Physics Letters* and is made available as an electronic reprint (preprint) with permission of The Authors (Published by AIP Publishing). The published version is available at: [<http://dx.doi.org/10.1063/1.4994022>]. One print or electronic copy may be made for personal use only. Systematic or multiple reproduction, distribution to multiple locations via electronic or other means, duplication of any material in this paper for a fee or for commercial purposes, or modification of the content of the paper is prohibited and is subject to penalties under law.

Downloaded on 26 Apr 2023 08:41:05 SGT

Unique lift-off of droplet impact on high temperature nanotube surfaces

Wei Tong,^{1,2,a)} Lu Qiu,^{1,2,a)} Jian Jin,³ Lidong Sun,^{3,b)} and Fei Duan^{1,c)}

¹*School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798*

²*Energy Research Institute @ NTU, Nanyang Technological University, 1 Cleantech Loop, 06-04 Cleantech One, Singapore 637141*

³*School of Materials Science and Engineering, Chongqing University, Chongqing 400044, China*

(Received 3 July 2017; accepted 22 August 2017; published online 1 September 2017)

A unique liquid film lift-off during a falling water droplet impacting on a heated titanium oxide nanotube surface has been experimentally revealed through a high speed visualization system. It is suggested that the Leidenfrost point on the nanotube surface has been significantly delayed, as compared to that on the bare titanium surface. Such delay is inferred to be a result of the increase in the surface wettability and the capillary effect by the nanoscale tube structure. By measuring the liquid lift-off distance from the substrate surface, a droplet lift-off is typically divided into four stages, namely, first contact, first lift-off, second contact, and second lift-off. The residence time at each stage is quantitatively evaluated. As the surface temperature increases, the duration time is significantly reduced for both the first contact and the first lift-off stages. *Published by AIP Publishing.*

[<http://dx.doi.org/10.1063/1.4994022>]

Contact boiling of a droplet impacting on a heated surface occurs when the surface temperature is high enough to activate nucleation sites to produce vapor bubbles. The dynamic boiling patterns, including splashing, spreading, bouncing, formation of secondary droplets, droplet disintegration, and levitation, have been intensively investigated.¹ When the surface temperature increases sufficiently high, the droplet would be prevented from touching the surface and reside on a stable layer of vapor generated by the droplet vaporization. The phenomenon is well recognized as the Leidenfrost effect.² According to the boiling patterns, different boiling regimes have been consequently identified as contact boiling, transition boiling, film boiling, etc.^{3,4} Due to the appearance of the Leidenfrost effect, the heat transfer between the droplet and the surface is interrupted, and thus, how to delay the transition to the Leidenfrost point has drawn extensive attention.^{5–7} Employment of surfaces with micro/nano-structures is one of the promising solutions because significant enhancement in nucleate boiling and improvement in the critical heat flux (CHF) have been achieved on such surfaces.^{8–10} The experimental works were carried out to investigate the effects on the Leidenfrost effect by using the surfaces with micro/nano textures or nanotubes. The transition between boiling regimes was discussed with the effect of the parameters such as impact velocity, surface temperature, and surface roughness on the transitions.^{11–15} Tran *et al.*¹² reported the dynamic boiling behaviors of a droplet impacting the heated micro-structured surface while varying the Weber number (We) from 1 to 1000 and the surface temperature from 200 °C to 550 °C and found that the dynamic Leidenfrost temperature was influenced by the pillar height. Further, a jet formation was also discovered within the contact boiling regime. In the experiments of Nair *et al.*,¹⁴ the solid surfaces covered with the carbon nanofibers

were capable of delaying the transition from contact boiling to film boiling. The delay was attributed to the cooling of the carbon nanofibers which was caused by the vapor flow just before the droplet impact. Thus, contact boiling was allowed to continue at much higher temperatures. Recently, Kim *et al.*¹⁵ stated that the Leidenfrost point was delayed by the presence of nanotubes on the target surface and an interesting explosion-like dynamics of a water droplet was found within the transient boiling regime. However, the dependence of such a boiling dynamics on the Weber number has not been systematically investigated. Thus, we conduct the experiments for a single falling water droplet to impact on a heated surface covered with titanium oxide (TiO₂) nanotubes in a wide range of Weber numbers. We observe a unique liquid film lift-off phenomenon due to the presence of the nanoscale tube structure.

Figure 1(a) shows the schematics of the experimental system. The droplets were generated from a flat-tipped needle (Gauge 32, Nordson EFD), which was connected to a syringe pump. The water flowed at a sufficiently small rate that allowed a droplet forming and falling from the tip of needle only when the surface tension could not hold the droplet due to gravity. The deionized water was employed as the working fluid with a density, ρ , of 998 kg m⁻³ and a surface tension, σ , of 72.0×10^{-3} N m⁻¹ at room temperature. The diameter and velocity of the droplet before its impact on the heated surface were measured from the images captured by using a high-speed camera (Phantom v711) at 22 000 frames per second with a 65 mm f/2.8–16 Canon lens. All the images were at a resolution of 640 × 480. The typical droplet diameter, D_0 , was 2.1 ± 0.01 mm, while the velocity, V , was varied by adjusting the height of the needle tip to the substrate, and accordingly, the Weber numbers ($We = \rho V^2 D_0 / \sigma$) were varied. In the current experiments, the Weber number was varied from 45 to 220. The dynamic wetting length, spreading diameter, lift-off distance, and the associated parameters were measured with the post-processing program of the camera. The titanium (Ti) substrate was tightly

^{a)}W. Tong and L. Qiu contributed equally to this work.

^{b)}Electronic mail: lidong.sun@cqu.edu.cn

^{c)}Electronic mail: feiduan@ntu.edu.sg

FIG. 1. (a) Schematics of the experimental system (not to scale) which consists of (1) water supply from a syringe pump, (2) flat-tipped needle, (3) high-speed camera, (4) lamp, (5) substrate surface of $10\text{ mm} \times 10\text{ mm}$ area, (6) temperature measurement point, (7) Ti substrate, (8) 10 mm thick rock wool layer, (9) copper holder, and (10) cartridge heater. (b) A scanning electron microscopy (SEM) image showing the TiO_2 nanotubes on a Ti surface. (c) Contact angle of 13° between a Ti surface coated with TiO_2 nanotubes and a water droplet with a diameter of 2.1 mm at room temperature. (d) Contact angle of 56° between a bare Ti surface and a water droplet with a diameter of 2.1 mm at room temperature.

clamped in a copper holder embedded with two cartridge heaters (Omega, Inc.). Only the substrate surface which has an area of $10\text{ mm} \times 10\text{ mm}$ is exposed to the ambient. The copper base is thermally insulated with 10 mm thick rock wool. A power supply was used to control the substrate surface temperature, T_w , to a fixed value ranging from 160°C to 500°C . T_w was measured by using a K-type fine diameter thermocouple (Omega, Inc.) embedded 1 mm below the center of the substrate surface. All the experiments were conducted under the conditions with a temperature of $26 \pm 1^\circ\text{C}$, a pressure of 1 atm, and a relative humidity of $48 \pm 5\%$.

The formation of TiO_2 nanotubes on the bare Ti substrate was achieved by the anodic oxidation technique. The details of the nanotubes' fabrication processes were reported by Sun *et al.*^{16–18} A scanning electron microscopy (SEM) image captured from the top view of the TiO_2 nanotubes is shown in Fig. 1(b). The nanotubes are with an average inner diameter of $48 \pm 7\text{ nm}$, an average outer diameter of $63 \pm 7\text{ nm}$, and an average height of $1.62 \pm 0.12\text{ }\mu\text{m}$. The presence of nanotubes leads to a significant reduction in the contact angle to 13° [see Fig. 1(c)] as compared to that of 56° on a bare Ti surface [see Fig. 1(d)]. The uncertainties were $\pm 4\%$ for the contact angle measurement. Aside from the increase in the surface wettability, the capillary effect can be induced by the nanoscale tube structure as well.¹⁵

The experiments have been conducted with the Weber numbers from 45 to 220 and the substrate surface temperatures from 160°C to 480°C for the nanotube surface and from 160°C to 500°C for the bare Ti surface. The droplet dynamic boiling behaviors during impacting were displayed by the side-view images. Figure 2 shows the historical images of the impact of a single water droplet on the substrate coated with TiO_2 nanotubes at the wall temperatures of 260°C , 300°C , and 360°C and on the bare Ti substrate at the surface temperatures of 260°C , 340°C , and 480°C , respectively. In all the six experiments, the Weber number is maintained at 45. The transitions among the boiling regimes are recognized through the dynamic boiling behaviors. Note that the images taken at 0 ms refer to the frame that the droplet was first seen to contact with the target surface. For both the surfaces at a lower temperature [see Figs. 2(a) and 2(d)] of $T_w = 260^\circ\text{C}$, the similar boiling behaviors are observed.

Shortly after impacting, the droplet contacts the substrate surface and spreads until the surface gets fully wetting after 2 ms. Heat is efficiently transferred to the liquid from the substrate, as a result of the occurrence of the contact boiling. However, if we have a closer view of the liquid boiling behaviors on the two kinds of surfaces, we can find the differences from three aspects: (1) when $t = 1\text{ ms}$, on the nanotube surface, the instability at the rim of the droplet spreading lamella indicates the formation of vapor bubbles

FIG. 2. Historical images of water droplet impacts on a nanotube surface with the wall temperatures of (a) $T_w = 260^\circ\text{C}$, (b) $T_w = 300^\circ\text{C}$, and (c) $T_w = 360^\circ\text{C}$ and on a bare Ti surface with the wall temperatures of (d) $T_w = 260^\circ\text{C}$, (e) $T_w = 340^\circ\text{C}$, and (f) $T_w = 480^\circ\text{C}$. In all the six experiments, the Weber number is 45.

at the solid-liquid interface; (2) when $t = 2$ ms, both the droplets get their maximum spreading. The surface gets pure wetting for the bare Ti substrate, whereas the tiny secondary droplet ejection due to the sudden vapor expansion is observed on the nanotube surface, indicating that the droplet thoroughly boils; and (3) when $t = 3$ ms, on the nanotube surface, the boiling continues with a nearly constant wetting length; however, a cutback phenomenon¹⁹ that results in a reduction of wetting area has been observed on the bare Ti surface, which in turn decreases the heat transfer between the solid surface and the liquid. The different behaviors indicate that the boiling is enhanced by the nanotube surface as compared to that by the bare Ti surface. In the boiling regime maps in Figs. 3(a) and 3(b), the boiling regime corresponds to the region indicated by the black squares.

As the wall temperature increases, a unique boiling behavior exhibits on the nanotube surface, as demonstrated in Fig. 2(b). Shortly after impacting ($t = 0.5$ ms), the meniscus shape is kept at the top of the droplet; however, a significant instability occurs at the droplet bottom without the obvious bubble ejection. Afterwards, as $t = 1$ ms, the droplet lifts off from the substrate surface and simultaneously spreads outwards as a liquid film till its maximum spreading when $t = 2$ ms. Later, the thin liquid film starts to retract while its disintegration is observed during this stage ($t = 3$ ms). The boiling behavior refers to the boiling regime in Fig. 3(a) depicted by the red circles, namely, the liquid film lift-off. However, this boiling behavior has never been observed on the bare Ti surface because the liquid film lift-off regime is absent. The transition to the consequent boiling regime starts from a lower surface temperature ($T_w = 340^\circ\text{C}$) on the bare Ti surface [see Fig. 2(e)] as compared to that on the nanotube surface ($T_w = 360^\circ\text{C}$) as shown in Fig. 2(c). The similar boiling patterns are observed on the two substrate surfaces. Formation of a liquid jet occurs during the droplet spreading period. Although the droplet still makes contact with the substrate, the wetting area is obviously decreased as compared to that in the contact boiling regime, which results in a longer evaporation time. Thus, the boiling regime can be treated as a transition boiling. In the boiling regime maps, it is described

by the blue triangles in Figs. 3(a) and 3(b). Besides, the transition temperature from the jet formation regime to the consequent boiling regime on the bare Ti surface is also lower than that on the nanotube surface. For the bare Ti surface, the maximum surface temperature of jet formation decreases with an increase in We ($T_w = 440^\circ\text{C}$ for $We = 45$ and $T_w = 360^\circ\text{C}$ for $We = 220$).

Figure 2(f) illustrates the vapor film boiling captured on the bare Ti substrate. In this boiling regime, the droplet does not touch the surface after the impact, and a vapor layer is formed between the surface and the droplet. The phenomenon only occurs when the surface temperature is above the Leidenfrost temperature. In the boiling regime map [Fig. 3(b)], the vapor film boiling regime is indicated by the green diamonds. The dashed line between the boiling with the jet formation regime and the vapor film boiling regime is consequently recognized as the dynamic Leidenfrost temperature of the bare Ti surface. For the nanotube surface, all the experiments end at the surface temperature of 480°C since the nanotubes go through phase transition accompanying the change in the nanoscale morphology when the temperature is above 500°C .^{20,21} We have not observed the vapor film boiling on the nanotube surface at the highest surface temperature of 480°C that we can reach in the experiments. However, we do have observed that the Leidenfrost point has been reached on the bare Ti surface at exactly the same temperature. Hence, there would be two possibilities: on the nanotube surface, the Leidenfrost temperature is higher than 480°C or no Leidenfrost effect can take place at all. Both scenarios are desirable in the related industrial applications.

If we focus on the unique lift-off phenomenon, we can find that the boiling is inevitable during the very short period after the contact, although the liquid film is levitated by its own vapor in a long-period observation. For instance, in the period of $t < 0.5$ ms in Fig. 2(b), the nucleate boiling is anticipated, which gives rise to the significant enhancement of wall-to-droplet heat transfer and the vigorous evaporation of the droplet. The reason could be that the improved wettability and the enlarged surface area by the nanotubes provide a considerably large amount of nucleation sites. The liquid,

FIG. 3. Boiling regime maps illustrated by We as a function of the wall temperature, T_w , of a single water droplet impacting (a) the heated nanotube surface and (b) the heated bare Ti surface with symbols indicating different boiling regimes: (black square) contact boiling, (red circle) liquid film lift-off, (blue triangle) boiling with jet formation, and (green diamond) vapor film boiling; Insets show the typical boiling patterns for each regime; (dashed line) transition boundary between regimes.

promptly attracted in the nanotubes by the capillary effect, goes through a fast nucleate boiling and forms a thin vaporized layer which simultaneously separates the droplet apart from the surface and lifts the spreading liquid film up. Figure 4 describes the evolution of the liquid film lift-off distance, denoted as h_{off} , for a droplet impact at a surface temperature of 380°C and We of 110. Here, h_{off} is defined as the vertical distance between the droplet and the substrate surface. The impact process can be divided into four stages, namely, first contact, first lift-off, second contact, and second lift-off. The first contact refers to the droplet residence after initial touch with the surface. During this stage, h_{off} is kept to be 0 mm. Then, the liquid droplet starts the first lift-off. Two apparent features can be observed: (1) The droplet is vertically lifted up synchronously with horizontal spreading at its bottom. The secondary tiny droplets are formed at the rim and laterally ejected upwards. The droplet seems to be cupped by a flat vapor cushion without the deformation of its top meniscus. (2) The droplet lifts up to a peak height of 0.22 mm and then it starts to fall down until gets a second contact with the surface. After the second contact, the droplet goes through a second lift-off with a continuous increase of h_{off} and hangs above the substrate as a thin liquid film. The liquid film finally retracts and disintegrates into small droplets. A visualization of the height evolution at different surface temperatures can be found in the [supplementary material](#) (video). Note that at lower temperatures (i.e., $T_w = 320^\circ\text{C}$ and $T_w = 340^\circ\text{C}$ for $We = 110$), the droplet impact only goes through two stages: the first contact and the lift-off [see Fig. 2(b)]. The inset of Fig. 4 shows the relationship between the wall temperature and the duration time of the first contact and the first lift-off. For the first contact, the duration time to initiate the lift-off decreases with an increase in the surface temperature. For instance, the droplet resides on the surface for 0.43 ms when the surface temperature is 320°C . But it is reduced to 0.09 ms when the surface temperature is 380°C . A similar trend in the duration time of the first lift-off stage is found as well.

FIG. 4. Evolution of the liquid film lift-off distance, h_{off} , from the substrate surface covered with TiO_2 nanotubes at $T_w = 380^\circ\text{C}$ with the Weber number of 110. The images show the typical stages of the droplet during impacting. The scale bar represents a length of 2 mm. The inset shows the wall temperature versus the droplet first surface contact and first lift-off duration time.

To sum up, a single water droplet which impacted on a Ti surface coated with TiO_2 nanotubes was experimentally investigated in a wide range of Weber numbers and surface temperatures. An interesting phenomenon was observed that the impinged droplet could be uniquely levitated as a liquid film by its own vapor on the nanotube surface. It was indicated that the nanotubes made significant contributions by improving the surface wettability and the capillary effects. The nanotubes dramatically increased the surface area and provided considerable nucleation sites which promoted the rapid vaporization of the liquid absorbed in the nanotubes and the consequent liquid film spreading and lift-off. With the lift-off phenomenon occurrence, the dynamic Leidenfrost point was significantly delayed on the nanotube surface. The lift-off characteristics were quantitatively explored. From the measurement of the liquid lift-off distance from the substrate surface, four stages were identified in a droplet lift-off process. For the first contact and the first lift-off stages, the duration time was found to decrease with an increase in the surface temperature.

See [supplementary material](#) for the video of EVideo showing the evolution of the liquid film lift-off distance with $We = 110$ and T_w ranging from 320°C to 400°C .

L.S. acknowledges the financial support from the National Natural Science Foundation of China (No. 51501024). F.D. would like to thank the support of NTU MAE Funding (M4082051).

- ¹A. Moreira, A. Moita, and M. Pano, *Prog. Energy Combust. Sci.* **36**, 554 (2010).
- ²J. Leidenfrost, *Int. J. Heat Mass Transfer* **9**, 1153 (1966).
- ³A. Wang, C. Lin, and C. Chen, *Phys. Fluids* **12**, 1622 (2000).
- ⁴T. Tran, H. J. J. Staat, A. Prosperetti, C. Sun, and D. Lohse, *Phys. Rev. Lett.* **108**, 036101 (2012).
- ⁵A. Yarin, *Annu. Rev. Fluid Mech.* **38**, 159 (2006).
- ⁶S. Herbert, T. Gambaryan-Roisman, and P. Stephan, *Colloids Surf., A* **432**, 57 (2013).
- ⁷J. D. Bernardin and I. Mudawar, *J. Heat Transfer* **121**, 894 (1999).
- ⁸K. N. Rainey, G. Li, and S. M. You, *J. Heat Transfer* **123**, 918 (2001).
- ⁹S. Ujereh, T. Fisher, and I. Mujumdar, *Int. J. Heat Mass Transfer* **50**, 4023 (2007).
- ¹⁰R. Chen, M. Lu, V. Srinivasan, Z. Wang, H. H. Cho, and A. Mujumdar, *Nano Lett.* **9**, 548 (2009).
- ¹¹A. Alizadeh, V. Bahadur, S. Zhong, W. Shang, R. Li, J. Ruud, M. Yamada, L. Ge, A. Dhinojwala, and M. Sohal, *Appl. Phys. Lett.* **100**, 111601 (2012).
- ¹²T. Tran, H. J. J. Staat, A. S. Arce, T. C. Foertsch, A. v. Houselt, H. J. G. E. Gardeniers, A. Prosperetti, D. Lohse, and C. Sun, *Soft Matter* **9**, 3272 (2013).
- ¹³G. C. Lee, J. Kang, H. S. Park, K. Moriyama, S. H. Kim, and M. H. Kim, *Exp. Therm. Fluid Sci.* **84**, 156 (2017).
- ¹⁴H. Nair, H. J. J. Staat, T. Tran, A. v. Houselt, A. Prosperetti, D. Lohse, and C. Sun, *Soft Matter* **10**, 2102 (2014).
- ¹⁵S. H. Kim, H. S. Ahn, J. Kim, M. Kaviany, and M. H. Kim, *Appl. Phys. Lett.* **102**, 233901 (2013).
- ¹⁶L. Sun, S. Zhang, X. W. Sun, X. Wang, and Y. Cai, *Langmuir* **26**, 18424 (2010).
- ¹⁷L. Sun, X. Wang, M. Li, S. Zhang, and Q. Wang, *Langmuir* **30**, 2835 (2014).
- ¹⁸L. Sun, S. Zhang, X. Wang, X. W. Sun, D. Y. Ong, and A. K. K. Kyaw, *Energy Environ. Sci.* **4**, 2240 (2011).
- ¹⁹S. G. Kandlikar and M. E. Steinke, *Int. J. Heat Mass Transfer* **45**, 3771 (2002).
- ²⁰Y. Yang, X. Wang, and L. Li, *J. Am. Ceram. Soc.* **91**, 632 (2008).
- ²¹O. K. Varghese, D. Gong, M. Paulose, C. A. Grimes, and E. C. Dickey, *J. Mater. Res.* **18**, 156 (2003).