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2015

Qiu, L., Dubey, S., Choo, F. H., & Duan, F. (2015). Splashing of high speed droplet train impinging on a hot surface. *Applied Physics Letters*, 107, 164102-.

<https://hdl.handle.net/10356/80890>

<https://doi.org/10.1063/1.4934531>

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Citation: [Applied Physics Letters](#) **107**, 164102 (2015); doi: 10.1063/1.4934531

View online: <http://dx.doi.org/10.1063/1.4934531>

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Splashing of high speed droplet train impinging on a hot surface

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(Received 25 June 2015; accepted 11 October 2015; published online 22 October 2015)

Transition phenomena are observed when a water droplet train (with up to 18.9 m/s in velocity and 39.20 kHz in frequency) impinges onto a heated copper surface (up to 250 °C). The hydrodynamic flow pattern strongly depends on the wall temperature. The surface temperature does not apparently influence the spreading speed when the wall temperature is less than the boiling temperature, but it enhances the spreading rate significantly at higher surface temperatures. A “steady-state” wetting surface area can be reached when the water supply rate equals the water consumption rate. The time-independent spreading diameter decreases with an increase in the wall temperature until an ultimate diameter of the “steady-state” wetting area is observed at around 0.4 mm, 3.4 times the droplet diameter, when the surface temperature is higher than 190 °C. Moreover, unlike the random direction splashing when wall temperature is less than 180 °C, a stable splashing angle is established at higher wall temperatures. However, the angle reduces apparently with the increase in the wall temperature. © 2015 AIP Publishing LLC.

[<http://dx.doi.org/10.1063/1.4934531>]

Related to the fundamental physical nature of impingement of a single droplet onto a solid surface, the phenomena including droplet spreading, splashing, rebounding, and forming of crown and secondary droplets have been widely investigated. On a dry surface under ambient temperature, the effects of droplet parameters^{1,2} and the surface conditions^{3–5} on the droplet impingement pattern have been explained both experimentally and numerically. The impinging droplet was described through Weber number, Reynolds number, and Ohnesorge number, while the surface condition was described through the roughness and wettability. The target surface with lower^{6,7} or higher^{7–13} temperature presented different hydrodynamic patterns, which resulted from the different surface conditions and evaporation rates. Alizadeh *et al.*⁷ reported the evolution of spreading diameter and contact angle during impingement as the temperature of flat and textured surfaces ranged from –15 °C to 85 °C. Manzello and Yang⁸ employed a wax surface with a temperature of 60 °C. In the experiments of Shen *et al.*,⁹ the wall temperature exceeded the boiling point. Boiling made the hydrodynamic characteristics of droplet impingement even more complex. Chandra and Avedisian¹⁰ investigated the droplet impingement on a ceramic porous surface and on a stainless steel surface with a maximum surface temperature of 250 °C. Khavari *et al.*¹¹ investigated the impact of a single droplet onto a high temperature glass substrate (around 350 °C) and observed an interesting fingering boiling pattern before the Leidenfrost point. The wall temperature in the experiments of Seki *et al.*¹² and Chen and Hsu¹³ reached 413 °C and 550 °C, respectively. The evolution of the wall temperature and the wall heat flux was reported. Significant attention has been given to the single droplet impingement investigations. However, in many industrial applications,

such as printing, coating, spray cooling, and metal processing,¹⁴ the continuous droplets are impinged onto the target surfaces. The interaction between the droplet impingements can render various phenomena. Accordingly, a droplet train, as a simplified view from the engineering application, has been studied further. Trujillo *et al.* numerically and experimentally investigated the impingement of a droplet train onto a wet hot surface with the HFE-7100 fluid.^{15,16} An iso-flux thermal boundary condition was generated by a thin-film heater. After the initial transient phase, a statistically stationary state was reached. The dimensions of the continuously generated craters and rims were basically stable. The droplet impingement led to the heat transfer inside the crater higher than the area outside the crater. However, the wall temperature in the vicinity of the impingement zone was not high enough to initiate significant boiling. Thus, we conducted the droplet train impingement experiments at the high wall temperature, which was much higher than the boiling temperature of the fluid.

A droplet train generator from FMP Technology GmbH, Germany, was applied to generate a stable, continuous, and high-frequency droplet train vertically downward. The deionized water was used as the working fluid. In this work, a pinhole plate with a diameter of 50 μm was assembled on the droplet nozzle. The frequency of the continuous droplets, f , was adjusted to 39.20 kHz while the upstream gauge pressure was around 24.5 psi. According to the measurements from the captured photos, the mean droplet diameter was 0.117 ± 0.0039 mm, while the mean droplet velocity was 15.15 ± 0.41 m/s. Therefore, the Weber number and Reynolds number of droplet were 374 and 1998, respectively. Aside from this baseline test, experiments were also conducted at higher (18.9 m/s) or lower (11.4 m/s) droplet velocities. The generated droplet train was then impinged onto a horizontal heated copper surface, which was furnished

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FIG. 1. The evolution of the diameter of the wetting area on the copper at different surface temperatures as the droplet velocity is 15.2 m/s.

by a sand paper (#1200). The surface roughness was measured with a surface profile scanner (Talyscan 150), and the area roughness parameter, S_a , the three-dimensional average arithmetic roughness, was $0.257 \mu\text{m}$. The wall temperature, T_w , was measured with the embedded calibrated thermocouples. Cartridge heaters were assembled from the bottom of the copper rod to vary the wall temperature from ambient temperature to around 250°C . The experiments were conducted in an open surrounding with a temperature of $26 \pm 1^\circ\text{C}$, a pressure of 1 atm, and a relative humidity of $48 \pm 5\%$. A high-speed camera (Phantom v711), mounted with a 65 mm f2.8-16 lens, was used to capture the images with 14 000 frames per second at a resolution of 1024×512 . The exposure time was set to be $1 \mu\text{s}$. An additional light-emitting diode lamp was used to supply sufficient light. To calibrate the camera, a ruler with 2.00 mm length was placed on the plane of focus as the reference. The spreading diameter and the splashing rebound angle were measured with the post-processing program of the camera. The maximum post-processing uncertainties were $\pm 5\%$ for the spreading diameter and ± 0.063 rad for the rebound angle.

When the droplet train was continuously, vertically impinging onto the target surface from the top, the evolution of the wetted area diameter on the solid surface was recorded. Figure 1 shows that the instantaneous spreading diameter increases as a function of time due to the continuous water droplets supply. However, the increasing rate of the spreading diameter slows down and then approaches a constant value. For example, after a spreading period of around 20 ms in the 163°C case, the spreading diameter increases to around 1.5 mm and reaches the “steady state.” This steady-state spreading diameter is independent of time. This steady status is reached once the water supply rate equals the water consumption rate caused by evaporation, splashing, etc. When the wall temperature is 26°C or 71°C , the main way to remove the water mass away from the surface is evaporation. Thus, the steady-state wetting area should be significantly large since the evaporation is relatively slow compared to the water supply. At higher wall temperatures (185°C or 211°C), the steady state is reached almost instantly after the first droplet impinges onto the surface. The steady-state spreading diameter reduces to around 0.4 mm only. The spreading speed is greatly accelerated by increasing the wall temperature. Figure 2 reveals the reasons of the aforementioned phenomena. The liquid-solid contact angle is relatively large when the wall temperature is less than the boiling point of water. Therefore, the surface is hard to be wetted efficiently, and the spreading speed is low. When the wall temperature increases to 131°C , the contact angle is dramatically reduced so that the spreading speed becomes faster. Besides, a significant boiling phenomenon is observed on the wetting surface. Vapor bubbles are generated randomly, which grow up, and are finally broken into tiny fractions for splashing. Aside from the evaporation, the bubble break-up induced water splashing makes a great contribution to the removal of the water mass away from the surface. When each bubble breaks, the boundary of the water film on the surface is broadened due to the “explosion”, which results in a higher spreading speed. The direction of the splashing in this regime seems to be random. It can be seen that the mechanism of the spreading of a droplet train is very different from that of

FIG. 2. The hydrodynamic pattern evolution at the surface temperatures of 26°C (a), 131°C (b), and 211°C (c) during the droplet train was impinging on the surface from 0 ms to 40 ms as the droplet velocity is 15.2 m/s.

a single droplet impingement. It is well established that the surface condition influences the maximum spreading diameter and the rebounding height apparently in the single droplet impingement experiments. The wettability of the target wall and the surface tension of the droplet are responsible for the results. However, in the droplet train study, the spreading is mostly caused by a mild increase in water bulk once the wetted area is sufficiently large (see Figure 2(a)).

Both the water evaporation and the splashing that are induced by boiling are elevated as the wall temperature increases. Therefore, the steady-state wetting area decreases apparently with an increase in wall temperature (see Figure 3). When the wall temperature is higher than 135 °C, the boundary of the steady-state wetting area falls into view of the camera so that we can measure. For example, the spreading diameter of the steady wetting area is around 4.5 mm when the wall temperature is 135 °C, but it reduces to around 0.4 mm when the wall temperature is higher than 190 °C. A further increase in the wall temperature does not reduce the spreading diameter apparently. The steady-state spreading diameter reaches a constant. For the baseline test, after we increased the wall temperature to the maximum and completed the first series of experiments, the wall was cooled down and the experiments were repeated. It shows that two sets of experiments agree very well and these results are reproducible. Moreover, the droplet velocity, which varied from 11.4 m/s to 18.9 m/s, does not influence the results.

Figure 4 shows the different hydrodynamic patterns at the various wall temperatures. The vapor bubble break-up induced water splashing becomes more significant when the wall temperature is increased up to 180 °C. Since the wetted area is getting smaller, the probability of collision between the randomly splashed tiny droplets with the upstream fine droplets significantly increases, which makes the droplet train abnormal (not showing in the figures). When the wall temperature is higher than 180 °C, a “stable” splashing angle, marked in Figures 4(e) and 4(f), is observed. The droplets are impinging on the hot surface and splashed into tiny droplets. These tiny droplets rebound radial outwardly with a specific angle with respect to the surface. Unlike the random direction

FIG. 3. The “steady-state” spreading diameter varies as a function of the wall temperature.

FIG. 4. The steady-state hydrodynamic patterns at the different surface temperatures of 120 °C (a), 139 °C (b), 152 °C (c), 179 °C (d), 192 °C (e), and 206 °C (f) as the droplet velocity is 15.2 m/s.

splashing when the wall temperature is less than 180 °C, the orderly rebound and splashing are axis-symmetrical at higher wall temperatures. Since the direction of splashing is relatively uniform, there is almost no collision between the splashed tiny droplets with the upstream fine droplets. The stable splashing angle varies with the wall temperature apparently. As shown in Figure 5, the rebound angle generally decreases with an increase in the wall temperature. The baseline test results show that the angle is around 0.6 rad when the wall temperature is in the range between 180 °C and 190 °C, and then reduces to around 0.2 rad when the wall temperature increases to 210 °C. A further increase in the wall temperature does not significantly influence the angle. Again, we repeated the baseline experiment and proved that these results were reproducible. Moreover, increasing the velocity to 18.9 m/s does not influence the results apparently, but reducing it to 11.4 m/s slightly delays the angle transition and then ends at a higher value. Currently, this transition is not able to be explained theoretically. However, according to the recent investigation that was reported by Khavari *et al.*,¹¹ the transition of the splashing angle might be related to the “fingering boiling” phenomenon, which is a sign of reaching the Leidenfrost point.

FIG. 5. The splashing angle reduces when the wall temperature increases.

To sum up, the interesting phenomena were observed when a high speed and frequency droplet train impinged on a high temperature target surface. The hydrodynamic flow pattern strongly depended on the wall temperature. First, the wall temperature varied the surface wettability and then influenced the spreading speed. The transient results showed that the surface temperature did not influence the spreading speed apparently when the wall temperature was less than the boiling temperature, but it enhanced the spreading speed significantly at higher surface temperatures. Second, the area of steady-state wetting surface decreased with an increase in the wall temperature. An ultimate diameter of the steady-state wetted area was found to be around 0.4 mm (3.4 times the droplet diameter) when the surface temperature was higher than 190 °C. Finally, unlike the random direction splashing when the wall temperature was less than 180 °C, a stable rebound angle was established at higher wall temperatures. The angle reduced apparently with the increase in the wall temperature. The transition of the splashing angle might be a sign of reaching the Leidenfrost point. Effects of various detailed parameters, such as droplet velocity, droplet size, impact angle, etc., can be further studied for a deep understanding of the transitions of the spreading diameter and rebound angle for the droplet train impingement.

The authors would like to thank National Research Foundation, Energy Innovation Programme Office, and Energy

Market Authority (EMA) of Singapore for their full support for the work carried out in this paper under a research Grant No. NRF2013EWT-EIRP001-017.

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