J Vis (2010) 13:41–47
DOI 10.1007/s12650-009-0010-9

REGULAR PAPER

Satoshi Someya · Satoshi Yoshida · Koji Okamoto · Yan Rong Li ·
Manabu Tange · Mohammad Mezbah Uddin

Jet ejection from droplets near the Leidenfrost temperature

Received: 21 April 2009 / Revised: 7 July 2009 / Accepted: 12 July 2009 / Published online: 12 December 2009

Abstract Droplets impinging on a hot surface that is near the Leidenfrost temperature were experimentally investigated. Ejection of jets from the top of the droplet was observed during the transient interaction between the droplet and a hot wall. We term this phenomenon jet ejection from droplets. When the bottom of the droplet initially impacts the hot surface, a jet is to be ejected from the top of the droplet. The jet ejection occurred only at low impact velocities and around the wetting limit temperature. It was not observed when droplets were dropped from large heights or when the surface was at a high temperature.

Keywords Boiling · Leidenfrost · Droplet

1 Introduction

In this letter, we report on the ejection of jets from the top of a droplet during the transient interaction between the droplet and a hot plate that is near the Leidenfrost temperature.

The interaction between a droplet and a hot plate is very significant when considering various kinds of boiling phenomena. Boiling phenomena on hot surfaces are of great interest for heat removal on micro- or macro-scales (Wachters and Westerling 1966; Labeish 1994). Boiling heat transfer characteristics are frequently represented using an evaporation curve (see Fig. 1a) in which the evaporation time (lifetime) of the droplet is plotted as a function of the temperature of the solid surface. The boiling characteristics depend on the roughness of the solid surface (Bernardin et al. 1997a), the wettability of the surface, the velocity of the droplet, the properties of the liquid (Labeish 1994; Jia and Qiu 2003; Wang et al. 2000), and even on the manner in which the liquid is dropped (Nejad et al. 2003). Boiling phenomena, especially those occurring near the Leidenfrost point, have been extensively investigated (Bernardin et al. 1997b; Wang et al. 2000; Emmerson 1975; Biance et al. 2003; Chizhov and Takayama 2004) in order to exploit the high critical heat flux (CHF) and to prevent fatigue of heat transfer surfaces.

For example, Richard et al. (2002) investigated the contact time of a Leidenfrost droplet and clarified that it depends on the droplet radius but not on the impact velocity. Chiu and Lin (2005) discussed the effects of the mass ratio of a compound droplet on energy dissipation and bounding behavior. Bertola and Sefiane (2005) clarified the behavior of droplets containing a polymer additive and investigated its effects on

---

S. Someya · S. Yoshida · K. Okamoto · Y. R. Li · M. Tange · M. M. Uddin
Department of Human and Engineered Environmental Studies, Graduate School of Frontier Sciences,
University of Tokyo, 5-1-5, Kashiwanoha, Kashiwa, Chiba, Japan

S. Someya (✉)
National Institute of Advanced Industrial Science and Technology, 1-2-1 Namiki, Tsukuba, Japan
E-mail: some@k.u-tokyo.ac.jp
Tel.: +81-4-71365872
Fax: +81-4-71364603

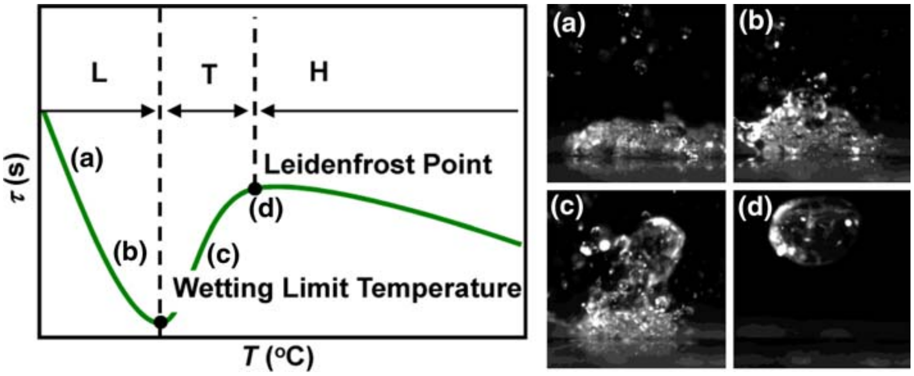

Fig. 1 Lifetime τ of a millimetric water droplet as a function of temperature *T* of a hot surface. *L* low-temperature region with nuclear boiling, *H* high-temperature region with film boiling, *T* transition region. Images were captured using a high-speed camera at 3 × 104 frame/s. They show near-instantaneous droplet evaporation at 200 ms after impact on surfaces at 200, 230, 260 and 290°C

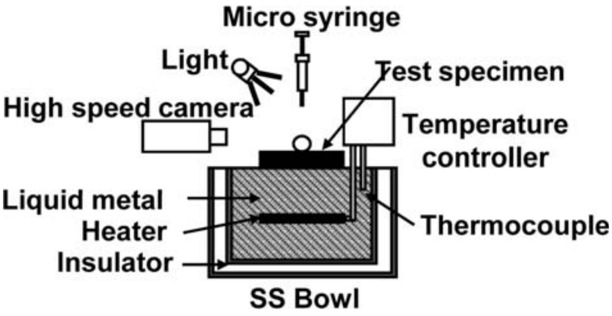

Fig. 2 Schematic of the experimental setup

secondary atomization near the Leidenfrost point. Many studies have investigated the impact dynamics for a large impact velocity (Richard et al. 2002; Bertola and Sefiane 2005) or for a superhydrophobic surface (Chen et al. 2007; Bartolo et al. 2007; Wang et al. 2007).

In this letter, we investigate the evaporation processes at the temperature range from 150 to 265°C, especially near the wetting limit temperature (240–260°C). While many researchers have investigated various characteristics of boiling near the wetting limit temperature, we experimentally observed an unreported phenomenon, namely ejection of a jet from the top of a droplet, called jet ejection here. The jet ejection occurred at 240–260°C. To investigate the boiling drop behavior is important not only in view of physical interests but also in view of a practical spray cooling system with the secondary atomization like a steel quanting, cooling electronic components, a fire fighting and so on. The present paper concentrates on reporting the new finding of jet ejection.

2 Experimental setup

The experimental system used consisted of a heating base for the plate, a temperature controller, a droplet generator, and a high-speed imaging system (see Fig. 2). A stainless steel (SUS304) plate was used as the hot surface (30 × 30 × 0.25 mm^3). It was floated on a liquid metal (U-alloy, melting point: 138°C) that was heated by an electric heater. Two SUS304 plates with different surface roughnesses were used. Other plates made from materials besides SUS304 were also used (SUS316, aluminum, copper, Hastelloy, Zircaloy, titanium oxide, and strontium oxide). However, jet ejection was observed only using the SUS304 plate with the large surface roughness. In order to clarify the mechanism of the jet ejection, more experiments should be done using different materials with controlled uniform roughness and using a SUS304 plate with controlled different roughness, while the present report concentrates on reporting the new finding of “jet ejection”. Consequently, only results obtained using SUS304 are given in the present letter.

The test plate was stored in a small container that was filled with the liquid metal. This small container was put inside a big container that was also filled with the liquid metal. The outside of the large container was wrapped with a thermal insulator. The temperature of the liquid metal was monitored using a K-type thermocouple and was controlled by PID control. Another thermocouple was used to monitor the temperature of the liquid metal near the free surface in the small container. All thermocouples were calibrated using a standard glass thermometer. The temperature of the liquid metal was almost uniform throughout the liquid. The uncertainty in its value was ±0.7°C and the temperature fluctuation was less than ±0.2°C. The temperature of the hot solid surface was calibrated using a thermocouple which was spot-welded on the surface. The measured value was 1.0% (about 2°C) less than the temperature of the liquid metal measured near the free surface in the small container. The droplet generator consisted of a microsyringe pump, a syringe and a PEAK tube. The working fluid was commercial distilled water and the initial temperature was set to 20°C. A droplet was formed and dropped carefully. The average diameter of the droplet was 2.5 mm.

A high-speed camera (Fastcam-APX RS 250 K, Photron Co., Ltd.; 1,024 × 1,024 pixels at 3,000 frame/s) and three 250-W metal halide lamps were used for visualizing the evaporation of the drops. The light illuminated the hot plate continuously. The falling droplet was recorded at 5,000 fps. The special resolution was 1,024 × 512 pixels^2 and it corresponds to 49.2 (height) × 24.6 (width) mm^2, about 48 μm/pixel. The droplet diameter was 52 pixels and the uncertainty was ±1 pixel. When the vapor clouds in a droplet were observed, the image was recorded at 60,000 fps, in which condition the special resolution was 128 × 128 pixels^2, 2.7 × 2.7 mm^2 (21.1 μm/pixel). A trigger signal for recording images at the moment of the drop impact was supplied by an optical sensor and a condensed LED light. When the drop fell across the LED light near the hot solid plate, the sensor sent a TTL signal to camera as a midpoint trigger and the camera recorded just before and after the impact. The droplet impact velocity was calculated from the initial height of the droplet as a free fall and also the recorded image.

3 Results and discussion

Table 1 shows the surface roughnesses of the two plates. Plate 2 had a much larger surface roughness than plate 1. Figure 3 shows the measured droplet lifetimes on plate 1 for droplets dropped from different heights

Table 1 Standard deviations of the surface roughness of SUS304 test pieces as measured by AFM

	R_a (nm)	R_{max} (nm)	R_z (nm)
Plate 1	9.624	119.1	37.49
Plate 2	140.2	617.5	422.3

R_a, the average center-line roughness; R_{max}, the maximum pitch difference; R_z, the 10-point average roughness

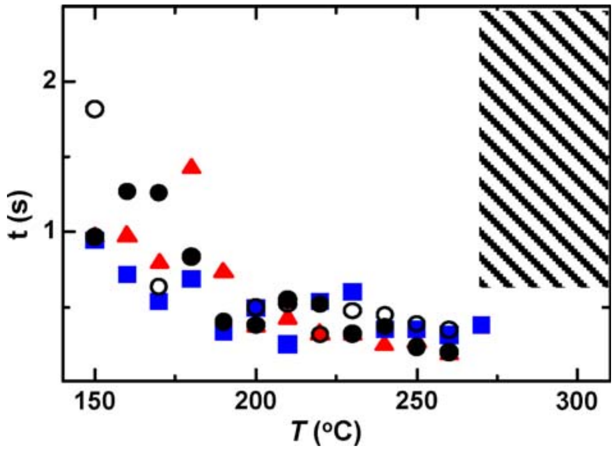

Fig. 3 Measured droplet lifetime (τ) at different initial temperatures of the hot surface (T). The lifetime is defined as the time from impact until the droplet was no longer visible. Plate 1 was used as the hot surface, droplets with diameters $d = 2.5$ mm were dropped from three different heights (H), which are denoted by different symbols [$H/d = 4$ (*filled circle*), 6 (*filled triangle*), 8 (*filled square*)]. The *shaded region* roughly indicates the Leidenfrost regime for plate 1. The results for plate 2 ($H/d = 6$ (*open circle*), $d = 2.5$ mm) are also shown

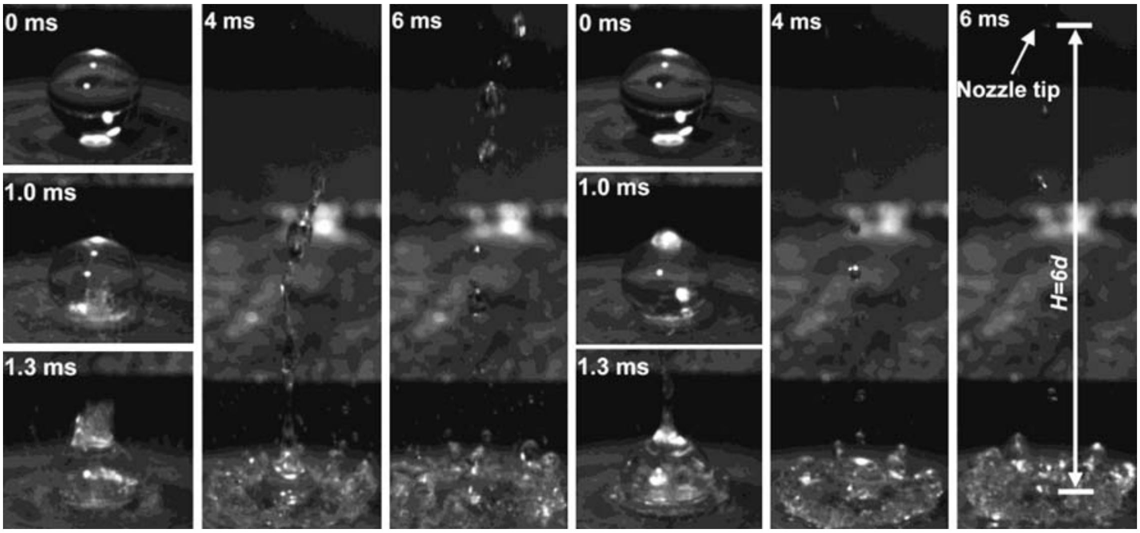

Fig. 4 *Left* Time sequential images of droplet behavior during jet ejection. The temperature of the hot surface (plate 2) was $T = 240$°C. The droplet velocity just prior to impact with the surface was $V = 0.54$ m/s, the Reynolds number was Re = 2,439, and the Weber number was We = 16.5. A portion of the water reached the highest point, which was close to the droplet release point ($H/d = 6$), 6 ms after impact with the hot surface. *Right* images for $T = 260$°C

and those for plate 2 at $H/d = 6$. An inclined plate (Chiu and Lin 2005; Yao and Cai 1988; Kang and Lee 2000) and a depressed plate (Mitsutake et al. 2004) have been used in previous studies to prevent the droplet from escaping and to enable the evaporation time to be easily determined. However, a flat surface was selected in our experiments to enable the instantaneous droplet behavior to be imaged at impact. Heated droplets were easily able to leave the hot plate and the viewing area at temperatures over the Leidenfrost point. The measured evaporation time at temperatures lower than the Leidenfrost temperature decreased with an increase in the surface temperature irrespective of the height the droplet was dropped from or the surface roughness of the plate. These two effects produced observable differences in the evaporation time in our experiments, but these differences were not large at temperatures below the Leidenfrost temperature.

The jet ejection was observed when plate 2 was used as the hot surface near the wetting limit temperature and a little below the Leidenfrost point. The jet ejection occurred at 240–260°C and was not observed at less than 240°C or at over 260°C. The wetting limit temperature was between 260 and 265°C. The Leidenfrost temperature was a little higher than 265°C though the Leidenfrost temperature could not be precisely measured because the droplet splashed on the flat surface. The reproducibility of jet ejection was high (around 80%), thus demonstrating that it was not an accidental phenomenon, while the ejected drop size and rising height were not uniform. Time sequential images during jet ejection are shown in Fig. 4. The temperatures of the hot plate were 240°C (left) and 260°C (right). The Weber number was estimated to be 16.5 by assuming a density of 960 kg/m^3 and a surface tension of 59 mN/m at 99°C. When the surface was 240°C, a vapor cloud was formed at the bottom surface of the droplet 1.0 ms after contact with the hot surface. This vapor pierced the top of the droplet at 1.3 ms and caused the water column to elongate vertically. A portion of the water reached the highest point, which was close to the droplet release point ($H/d = 6$), 6 ms after impact with the hot surface. When the surface was 260°C, the vapor cloud reached the top of the droplet pierced the droplet surface at 1.0 ms. A jet was ejected sooner at the higher temperature.

In our experiments, jet ejection occurred only at low impact velocities ($V = 0.54$ m/s) and around the wetting limit temperature, $T \approx 240$–260°C. When the falling height and the impact velocity were large, the droplet splashed and the jet ejection was not observed. Factors that could determine whether jet ejection occurs were droplet velocity, surface temperature, and surface roughness. The surface roughness could affect the contact angle and the total heat flow. Jet ejection was observed only with the plate with a rough surface (plate 2).

In order to gain a better understanding of droplet behavior during jet ejection, imaging using a higher frame rate and a higher magnification was performed immediately after impact. Figure 5 shows time sequential images of the interior of the droplet. As a result of using high-speed imaging, the movement of the vapor inside the droplet can clearly be seen. The liquid at the center of the droplet evaporates

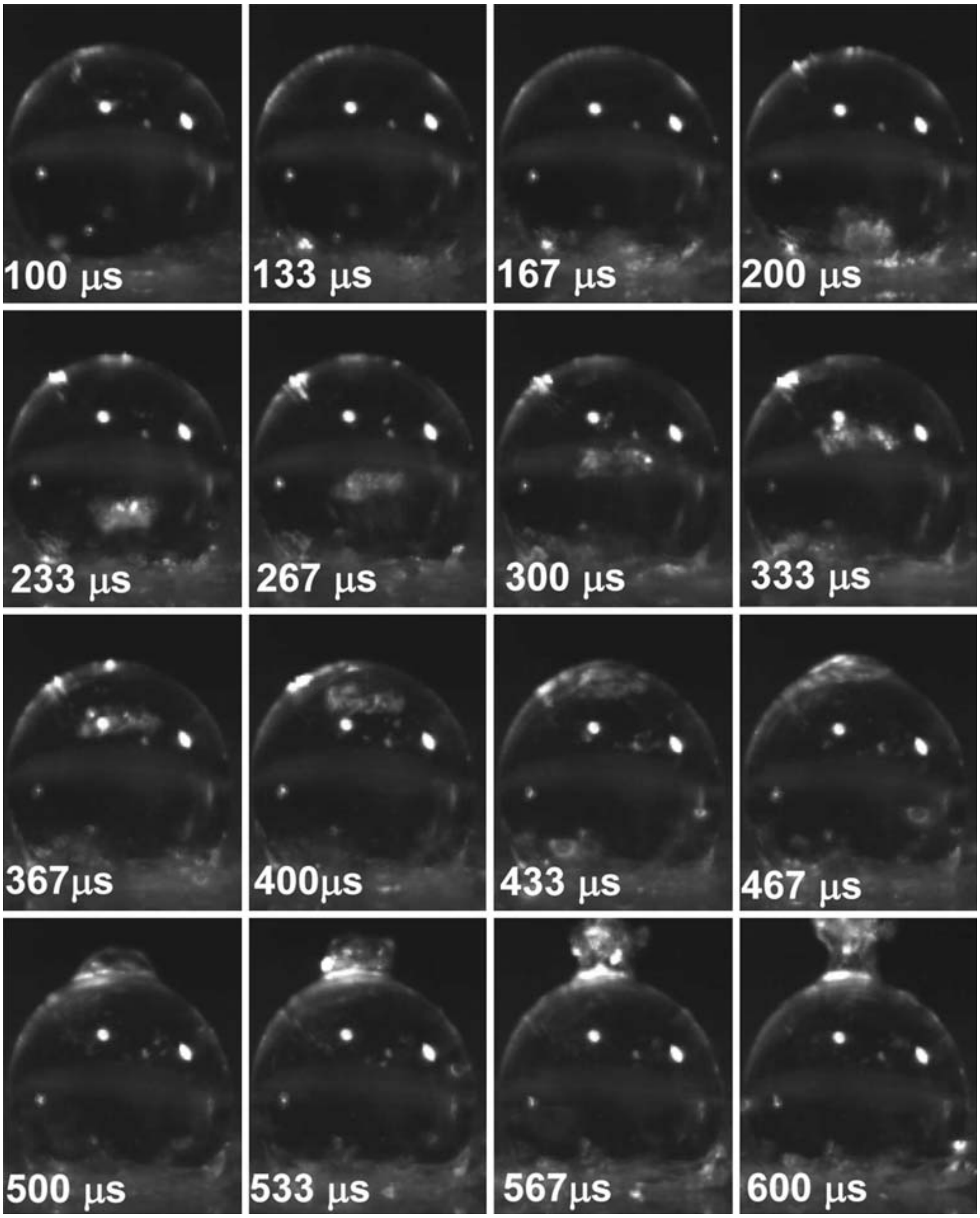

Fig. 5 Time sequential images of the droplet during jet ejection between 100 and 600 μs after the impact. These images were obtained almost parallel to the hot surface. They show the detailed behavior of the droplet. Experimental conditions were the same as those for Fig. 4 (*left*), with the hot plate at 240°C. Inside the droplet, the vapor cloud was generated due to rapid evaporation at the bottom interface of the droplet

immediately after making contact with the hot surface, forming a vapor. The vapor cloud was generated immediately after the droplet and the hot surface made contact. It then separated from the surface and rose vertically. It pierced the upper surface of the droplet, breaking the interface with the entraining liquid water. The speed of the vapor cloud was about 9.4 m/s, which is much smaller than the speed of sound in water. The vapor speed was estimated from images and its uncertainty was ±0.63 m/s. A pressure wave inside the droplet due to the vapor generation had been thought to cause the jet ejection before visualizing the vapor movement, however, the speed of the vapor rising and that of the pressure wave were quite different and they could not interact each other. Figure 5 supports this conjecture, although there are currently many unknowns.

Recently, Cossali et al. (2005, 2008) and Chaves et al.(1999) reported another jet-like phenomenon at a 10 times larger Weber number and with considerably larger surface roughnesses of Rz = 1.6 and 14.5 μm. The initial size of their droplets were in the range 2–4 mm. The impact velocities (determined by the height of the release point) were 7–10 times larger than those in our experiments. In their experiments about the secondary atomization of droplet, they observed a jet just after impact when the hot plate temperature was 230–260°C. They noted the phenomenon had quite random characteristics.

They observed the jet at high impact velocities. By contrast, jet ejection was never observed at high-impact velocities in our experiments. It is difficult to determine whether these represent the same phenomenon as the one we observed because they were not reported in detail in the above references.

Yao and Cai (1988) and Kang and Lee (2000) reported that the impact angle affected the droplet shape and the Leidenfrost point. Bernardin et al. (1997a, b) found that the surface roughness did not affect the CHF temperature but that it did affect the Leidenfrost point. Thus, both the roughness and the impact angle affect the Leidenfrost point. In both our and Cossali's experiments, the phenomena occurred only on rough surfaces. Jet ejection was not observed using seven other materials (SUS316, aluminum, copper, Hastelloy, Zircaloy, titanium oxide, and strontium oxide) having polished surfaces in our experiments. The surface roughness might be an important factor for determining whether jet ejection occurs.

The two jet phenomena were observed at quite different impact velocities. A more definite understanding of jet ejection requires a further investigation, since jet ejection was not observed at high impact velocities in our experiments. Bernardin et al. (1997a) found that the impact velocity did not affect the CHF temperature or the Leidenfrost point. Furthermore, according to Richard et al. (2002), the impact velocity did not affect the contact time. Thus, the impact velocity does not affect the total heat flow from the hot surface.

Another possible explanation for jet ejection could be the large subcooled boiling with micro bubble emission due to the large total heat flow at impact as a result of the rough surface. A small bubble was separated from a relatively large bubble which was generated at the impact point, and a small bubble rose up rapidly with condensation. The jet ejection occurs on rough surface and at large subcooled temperature. The temperature of falling droplet was near the room temperature (about 24°C) in our experiments though it was not monitored. In this point, the vapor rising in the jet ejection is similar to the large-subcooled boiling with micro bubble emission. However, the condensation of the vapor cloud in the jet ejection was not observed. In addition, the bubble speed and detail mechanism of the large-subcooled boiling with micro bubble emission are not clear at this time. Therefore, a more definite understanding of jet ejection requires a further investigation.

4 Conclusion

In conclusion, droplet jet ejection due to the rapid generation of a vapor cloud at the droplet center has been clearly visualized in experiments for the following conditions: an initial hot surface temperature of between 240 and 260°C with a large surface roughness ($R_{\max} = 620$ nm), and an impact velocity of 0.54 m/s. The vapor cloud was generated immediately after contact between the droplet and the hot surface. A small portion of the generated vapor rose from the hot surface and it pierced the upper surface of the droplet, resulting in ejection of a jet.

References

Bartolo D, Boudaoud A, Narcy G, Bonn D (2007) Dynamics of non-Newtonian droplets. Phys Rev Lett 99:174502

Bernardin JD, Stebbins CJ, Mudawar I (1997a) Effects of surface roughness on water droplet impact history and heat transfer regimes. Int J Heat Mass Transf 40:73–88

Bernardin JD, Stebbins CJ, Mudawar I (1997b) Mapping of impact and heat transfer regimes of water drops impinging on a polished surface. Int J Heat Mass Transf 40:247–267

Bertola V, Sefiane K (2005) Controlling secondary atomization during drop impact on hot surfaces by polymer additives. Phys Fluids 17:108104

Biance AL, Clanet C, Quere D (2003) Leidenfrost drops. Phys Fluids 15(6):1632–1637

Chaves H, Kubitzek AM, Obermeier F (1999) Dynamic processes occurring during the spreading of thin liquid films produced by drop impact on hot walls. Int J Heat Fluid Flow 20:470–476

Chen RH, Chiu SL, Lin TH (2007) Resident time of a compound drop impinging on a hot surface. Appl Therm Eng 27:2079–2085

Chiu SL, Lin TH (2005) Experiment on the dynamics of a compound drop impinging on a hot surface. Phys Fluids 17:122103

Chizhov AV, Takayama K (2004) The impact of compressible liquid droplet on hot rigid surface. Int J Heat Mass Transf 47(6–7):1391–1401

Cossali GE, Marengo M, Santini M (2005) Secondary atomisation produced by single drop vertical impacts onto heated surfaces. Exp Thermal Fluid Sci 29:937–946

Cossali GE, Marengo M, Santini M (2008) Thermally induced secondary drop atomisation by single drop impact onto heated surfaces. Int J Heat Fluid Flow 29:167–177

Emmerson GS (1975) The effect of pressure and surface material on the leidenfrost point of discrete drops of water. Int J Heat Mass Transf 18:381–386

Jia W, Qiu HH (2003) Experimental investigation of droplet dynamics and heat transfer in spray cooling. Exp Thermal Fluid Sci 27:829–838

Kang BS, Lee DH (2000) On the dynamic behavior of a liquid droplet impacting upon an inclined heated surface. Exp Fluids 29:380–387

Labeish VG (1994) Thermodynamic study of a drop impact against a heated surface. Exp Thermal Fluid Sci 8:181–194

Mitsutake T, KANO F, Oosato T, Sayano A, Akiba M, Morooka S (2004) Boiling heat transfer characteristics with highly wettable heated surface under forced convection conditions. JSME Int J Ser B 47(2):168–172

Nejad VM, Mostaghimi J, Chandra S (2003) Air bubble entrapment under an impacting droplet. Phys Fluids 15(1):173–183

Richard D, Clanet C, Quere D (2002) Contact time of a bouncing drop. Nature 417(20):811

Wachters LHJ, Westerling NAJ (1966) The heat transfer from a hot wall to impinging water drops in the spheroidal state. Chem Eng Sci 21:1047–1056

Wang AB, Lin CH, Chen CC (2000) The critical temperature of dry impact for tiny droplet impinging on a heated surface. Phys Fluids 12(6):1622–1625

Wang Z, Lopez C, Hirsa A, Koratkar N (2007) Impact dynamics and rebound of water droplets on superhydrophobic carbon nanotube arrays. Appl Phys Lett 91:023105

Yao SC, Cai KY (1988) The dynamics and Leidentfrost temperature of drops impacting on a hot surface at small angles. Exp Thermal Fluid Sci 1:363–371