Available online at www.sciencedirect.com
ScienceDirect
International Journal of Thermal Sciences 47 (2008) 229–236
International Journal of Thermal Sciences
www.elsevier.com/locate/ijts

Interaction phenomena of two water droplets successively impacting onto a solid surface

Hitoshi Fujimoto [a], Albert Y. Tong [b,*], Hirohiko Takuda [a]

[a] *Department of Energy Science and Technology, Kyoto University, Kyoto 606-8501, Japan*
[b] *Department of Mechanical and Aerospace Engineering, University of Texas at Arlington, TX 76019-0023, USA*

Received 13 July 2006; received in revised form 9 February 2007; accepted 11 February 2007

Available online 29 March 2007

Abstract

This study is concerned with the deformation behaviors of two droplets impinging successively onto a solid. Photographic means is used to understand the physics of the interaction phenomena between the two droplets. Water droplets of diameters between 0.39 and 0.65 mm with impact velocities ranging from 2.0 to 5.0 m/s are examined. The temperature of the solid surface is set at 25, 300 and 500 °C. The effects of solid surface temperature, droplet impact velocity and time interval between successive discharges on the collision behavior of the two successive impinging droplets are studied.

Keywords: Successive droplet collision; Weber number; Liquid crown; Surface temperature

1. Introduction

Spray jet impingement on solid substrates occurs in various industrial and environmental applications. The collision of a single droplet with a solid has been studied both empirically and theoretically as fundamental research in such applications [1–7]. A comprehensive review of related studies has recently been given by Yarin [8]. It has been reported that the deformation behavior of a single droplet impinging on a solid is influenced by many factors, such as impact velocity and pre-impact diameter of droplet, liquid viscosity, surface tension, wettability between liquid and solid surface, liquid and solid temperatures, roughness of solid surface, impact angle, etc. Among them, the Weber number associated with the impact energy of droplet and the solid substrate temperature play a key role.

The results obtained in the prior studies are very interesting from the aspects of fluid dynamics. The collision of a single droplet with a solid is, however, too ideal. In actual spray jets, there are numerous droplets randomly impinging onto a solid surface. Since the number density of droplets is relatively large in the vicinity of the solid surface, interactions (collisions) between droplets occur frequently. The physics of the phenomena is certainly more complicated in nature than the collision of a single droplet.

There are several studies published in the literature on the collision of multiple droplets with a solid. Yarin and Weiss [9] examined the successive impact of liquid drops onto a solid surface by using a CCD camera. Fujimoto et al. [10] studied the collision of a droplet with a static hemispherical droplet on a solid theoretically as well as experimentally. They also investigated the collision of two successive droplets with a solid at room temperature by means of numerical simulations [11] and photographic observations [12]. In [12], the effects of the distance between the two droplets on the collision behavior were examined with the droplet Weber number at around 50. Afterward, the collision of two successive droplets with a hot solid was investigated experimentally [13] under the conditions that the droplet Weber number was close to 100 and the temperature of the solid surface at 120, 300 and 500 °C. Karl and Frohn [14] studied the collision of a stream of droplets with a hot solid. Their experiments were carried out under the conditions of relatively low Weber numbers. Despite these prior studies, the interaction phenomena of droplets remain unclear.

* Corresponding author. Tel.: +1 817 272 2297; fax: +1 817 272 2952.
E-mail address: tong@uta.edu (A.Y. Tong).

1290-0729/$ – see front matter
doi:10.1016/j.ijthermalsci.2007.02.006

Nomenclature

d_p	pre-impact diameter of droplet	m
l	distance traveled by a droplet during a small time interval	m
v	impact velocity of droplet	$m\,s^{-1}$
We	Weber number	

Greek letters

ΔL	spacing between two droplets	mm
Δt	time interval	s
ρ	density	$kg\,m^{-3}$
σ	surface tension	$N\,m^{-1}$
τ	dimensionless time	

Subscripts

1	leading droplet
2	trailing droplet

All other symbols are defined where they appear

This study is concerned with the impingement of two successive droplets onto a solid. Photographic observations were performed where two water droplets impact coaxially onto a solid substrate at various temperatures. The pre-impact droplet diameter varies between 0.39 and 0.65 mm, and the droplet impact velocity ranges from 2.0 to 5.0 m/s. The surface temperature is set at 25, 300, and 500 °C. The effects of the Weber number, the temperature of the solid surface and the spacing between the two droplets on the collision dynamics were investigated in detail.

2. Experimental procedure

Fig. 1 depicts a schematic of the experimental apparatus used in the present study. The setup is similar to the one used in a previous study on the collision of successive droplets with a surface. A brief description of the experiment setup is given here; details can be obtained from [13].

Distilled water at room temperature is issued from a round nozzle with a vibrator in the form of a stream of droplets with uniform diameter and velocity. A rotating disk with a slit is used to control the number of droplets impinging onto the substrate underneath.

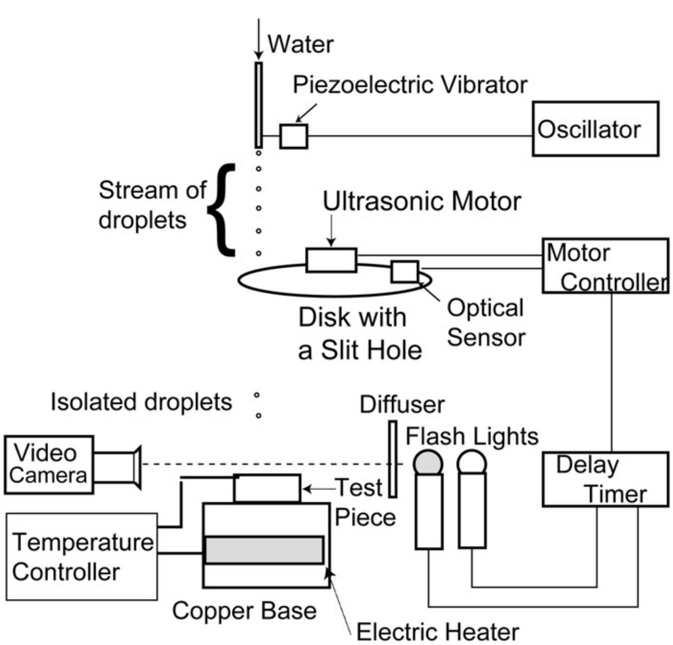


Fig. 1. Schematic of experimental setup.

A circular optical glass disk, 5 mm thick, 30 mm in diameter, is used as the test surface for the experiments at room temperature. Since the disk is produced for the purpose of optical experiments, it has an extremely smooth surface. The irregularity of the surface profile is within 100 nm (specified by manufacturer). For experiments at higher temperatures, Inconel 625 is used instead since the optical glass is fragile to thermal stresses. The test piece is a 6 mm thick disk, 28 mm in diameter. It is composed of a 1 mm thick Inconel 625 layer bonded to a 5 mm thick nickel-based alloy layer. The test piece is firmly mounted to the metal base. The 5 mm thick nickel-alloy layer enables the Inconel layer to remain rigid during the experiments. The mean surface roughness of the Inconel alloy is confirmed to be within 0.3 μm with its surface temperature maintained at a preset value by thermocouples and a temperature controller that regulates the voltage of the electric heater. The variation of the surface temperature is, however, observed to be within 10 °C of the preset value during the experiments.

The deformation process of droplets impacting successively on the solid is investigated by using a digital video camera equipped with a macro lens which has an effective resolution of 720 × 480 pixels. Since the time scale of the droplet collision process is very small (less than 1 ms) compared to the frame rate of the video camera (=1/30 s), the video camera is too slow to capture the droplet collision process. Photographs taken in sequence under the same experimental conditions are used instead. A backlighting method is used where two strobe lights are operated consecutively at a preset time interval such that double-exposure photographs of the droplets can be taken in sequence.

Samples of the double-exposure photographs showing the collision of two droplets impinging successively onto a hot solid are shown in Fig. 2. The images of droplets exposed at the first and second flash are indicated by the symbols <i> and <ii>, respectively. In (a), neither droplet has reached the solid surface even at the second flash. The pre-impact droplet diameters, (d_{p1}, d_{p2}), and the spacing in-between, ΔL, are measured directly from the photograph. The droplet impact velocities, (v_1, v_2), are determined simply by dividing the distance trav-

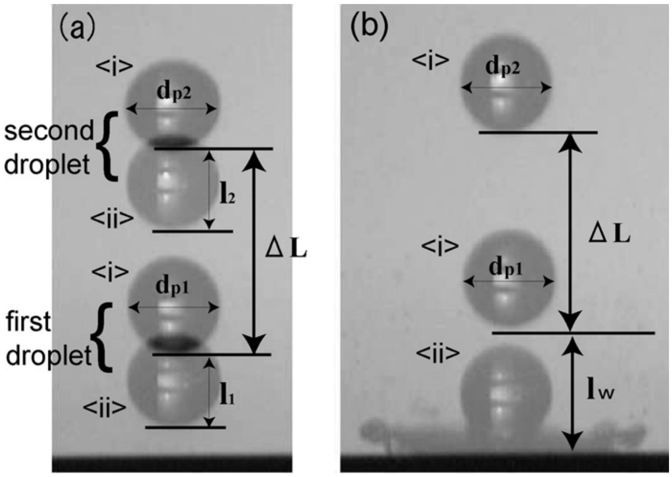


Fig. 2. Double exposure photographs of two successive droplets impacting on a hot Inconel alloy surface at 500 °C. (<i> first exposure; <ii> second exposure.) Pre-impact diameters of droplets are d_{p1}, $d_{p2} = 0.56$ mm, 0.56 mm; time interval Δt is 0.2 ms in (a) and 0.8 ms in (b).

eled by each droplet, (l_1, l_2) by Δt, the time interval between flashes, i.e.

$$v_i = l_i/\Delta t \quad (i = 1, 2) \tag{1}$$

Note that the time period, Δt, between the two consecutive flashes is longer in (b). The first flash occurs before the impact of droplets and the second flash is triggered after the impact.

In the present study, time t starts from the instant when the leading droplet first touches the solid. The distance, l_w, between the solid surface and the bottom of the first droplet taken at the first flash is measured to determine the time at which the first droplet impacts the solid. The time is calculated as l_w/v_1 after the first flash. It is estimated by using the time period between the two flashes, impact velocity of the first droplet and the distance, l_w, as follows

$$t = \Delta t - l_w/v_1 \tag{2}$$

Since the photographs were taken parallel to the solid surface, the sunken concaved shape of the liquid is not reviewed in the photographs. This should be kept in mind when the physics of the phenomena is discussed.

In the present setup, the diameter and velocity of the droplets as well as the inter-droplet spacing are controlled by the water flow rate, the nozzle diameter and the frequency of nozzle vibrator. But individual control of the variables cannot be made independently. Since the trailing droplet travels faster in the wake flow region behind the leading droplet [12], the inter-droplet spacing right before the impact can be adjusted, to some extent, by varying the elevation of the nozzle relative to the solid surface. However, wider spacing is difficult to attain experimentally.

It should be mentioned that it is technically difficult to have precise control of the impact conditions of droplets (pre-impact diameter of droplets, impact velocity of droplets, the spacing between two droplets) for the experiments. For any given experiment, the pre-impact diameter of droplets does not remain constant throughout the experiment, although the variation is slight.

Table 1
List of impact conditions examined in the present study

Temperature	Fig.	d_p or d_{p1}, d_{p2}, mm	v or v_1/v_2, m/s	We or We_1/We_2	Uncertainty of We
Room temperature	3(a)	0.56	2.55	49	47–53
	3(b)	0.59	4.55	165	156–174
	4	0.58/0.58	4.2/4.3	138/145	130–146/137–153
	5	0.57/0.39	2.3/2.4	41/30	38–44/28–33
300 °C	6(a)	0.59	3.95	124	117–132
	6(b)	0.59	3	72	67–77
	7	0.60/0.60	3.95/4.0	127/130	119–134/122–137
	8	0.54/0.54	3.0/3.1	66/70	61–70/65–75
	9	0.64/0.64	2.45/2.55	52/57	48–56/52–60
500 °C	10	0.64/0.64	2.35/2.45	48/52	44–51/48–56

This also applies to the impact velocity and the inter-droplet spacing which contribute additional uncertainties to the experimental data. To minimize the uncertainties, the pre-impact diameters of the droplets and the spacing between two droplets in every photograph are prescreened and irregular data are filtered out. In addition, irregular impact velocity of droplets can be identified from the droplet image at the first flash. If the impact velocity is too slow, the droplets will be located far above the solid surface at the first flash. On the other hand, if the impact velocity is too fast, the droplets would have already impacted on the solid at the first flash.

Dimensionless variables are employed in the present study. The pre-impact diameter and velocity of first droplet are used as the reference length and velocity. The dimensionless time, τ, is defined as

$$\tau = t/(d_{p1}/v_1) \tag{3}$$

and the Weber number is defined as:

$$We_i = \frac{\rho v_i^2 d_{p_i}}{\sigma} \quad (i = 1, 2) \tag{4}$$

where σ and ρ denote surface tension and liquid density, respectively.

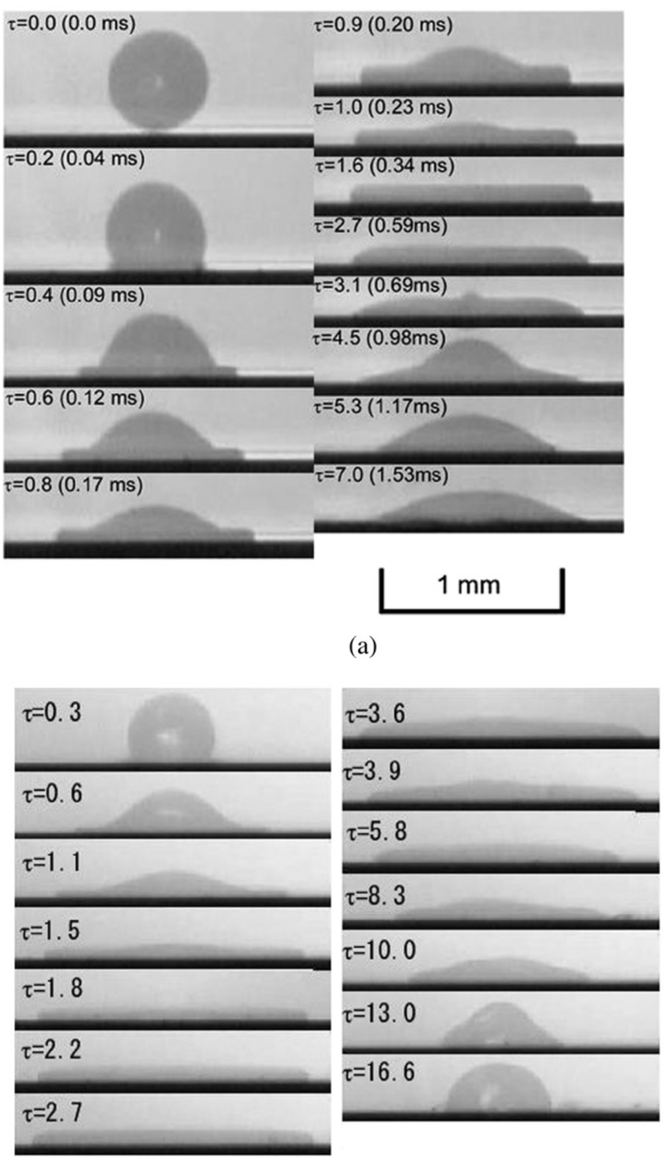
The experimental conditions shown in the present paper are listed in Table 1. Pre-impact diameters between 0.39 and 0.65 mm with impact velocities ranging from 2.0 to 5.0 m/s are examined. The temperature of solid surface is set to room temperature, 300 and 500 °C. Note that the accuracy of the length measurement is within 0.02 mm but is dependent on the magnification of the lens system. The accuracy of the impact velocity is within 0.05 m/s. The uncertainty range for the Weber number is listed in Table 1 and is wider for larger impact velocity.

This research is part of a continuous effort on the study of droplet collisions onto a surface. The physics of the phenomena with droplet impinging on a cold surface with Weber number at about 50 was first investigated [12]. It was followed by a subsequent study on the collision with a hot surface with Weber number at about 100 [13]. The emphasis of the present study is placed on the effects of the Weber number at various solid surface temperatures.

3. Results and discussion

3.1. Collision of water droplets with a solid at room temperature

The deformation behavior of a single droplet impacting on a solid surface at 25 °C is examined prior to the successive collision of droplets. Fig. 3 depicts a sequence of photographs showing the collision of droplets with a solid at room temperature for (a) $d_p = 0.56$ mm, $v = 2.55$ m/s ($We = 49$) and (b) $d_p = 0.59$ mm, $v = 4.55$ m/s ($We = 165$). In case (a), a circular liquid film is formed around the bottom of the droplet immediately after the impact at $\tau = 0.2$. It spreads radially along the solid surface from $\tau = 0.2$ to 1.0, while the height of the droplet decreases monotonically with time. The droplet is deformed into a thin circular disk at $\tau = 1.6$. The edge of the thin liquid disk becomes rounded due to the effect of surface tension. Afterward, the liquid disk begins to recoil. A reverse flow originating from the edge towards the center is shown at $\tau = 2.7$. It finally reaches the center axis at $\tau = 3.1$ when an upward swelling at the center begins. The height at the center axis increases as the upward swelling caused by the reversed flow continues. Eventually, at $\tau = 4.5$, the upward swelling ceases and an outward radial flow from the center begins. Similar recoiling and spreading motions occur repeatedly. Eventually, the liquid reaches a stationary state due to viscous dissipations.



(b)

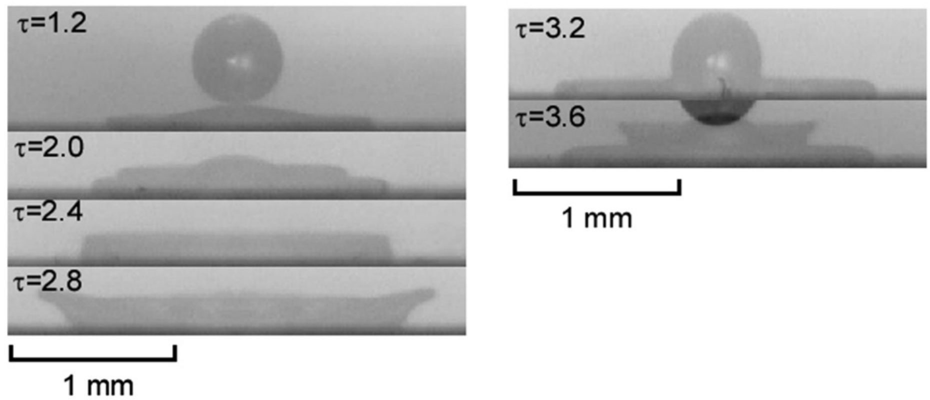
Fig. 3. Deformation behavior of a single droplet impacting onto a solid surface at room temperature (a) $d_p = 0.56$ mm, $v = 2.55$ m/s, (b) $d_p = 0.59$ mm, $v = 4.55$ m/s.

The deformation behavior of the droplet in case (b) shows a similar trend as in case (a). Since the Weber number of case (b) is approximately three times larger than that of case (a), it has a larger maximum spreading diameter [8]. It should be noted that disintegration of droplet would occur if the Weber number exceeds a certain value [3]. The condition at which disintegration of droplet would occur is also dependent on surface temperature and surface roughness [8]. However, the condition for droplet disintegration cannot be realized by the experimental setup of the present study.

The results of two droplets impinging successively onto a solid are examined. Fig. 4 presents the collision of two successive droplets on a solid at room temperature with $d_{p1} = 0.58$ mm, $d_{p2} = 0.58$ mm, $v_1 = 4.2$ m/s, and $v_2 = 4.3$ m/s ($We_1 = 138$, $We_2 = 145$). Note that ΔL, the spacing between the two droplets, is 0.8 and 1.6 mm in (a) and (b), respectively. Note that only the images after the impact of the second droplet are shown since information on the collision prior to that can be obtained from the results of the single droplet collisions. In (a), a circular liquid swelling appears around the bottom of the second droplet after the impact of the second droplet. It develops radially and axially as the height of the liquid at the center axis decreases. Eventually the liquid swelling reaches the outer edge and the coalesced liquid deforms into the shape of a crown.

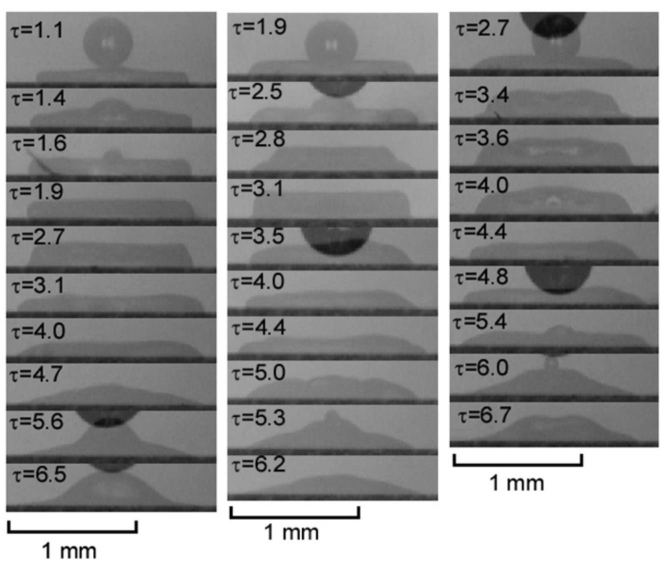
The formation of a liquid crown is a characteristic feature of successive collisions of droplets. A brief explanation of the process is included here. A more detailed discussion on the mechanism is given in [15]. When the second droplet impacts on the top of the first droplet, a high-pressure region appears near the impact point due to the difference of local velocities between the two droplets. A large pressure gradient normal to the free liquid surface gives rise to the circular liquid swelling. The velocity difference between the two droplets near the impact point is slight if the spacing between inter-droplet spacing is small. A higher circular liquid swelling can also be seen in (b).

It should be noted that experiments for the successive collision of droplets are very difficult to perform. It is not easy to ensure axi-symmetric flows in the experiments, particularly at large Weber numbers and at the later time stages. With increasing Weber numbers, appreciable asymmetry will develop sooner in the process. Therefore, the results at the later time stages are not shown in Fig. 4.



(a) (b)

Fig. 4. Deformation behavior of two droplets impacting successively onto a solid surface at room temperature for $d_{p1} = 0.58$ mm, $d_{p2} = 0.58$ mm, $v_1 = 4.2$ m/s, $v_2 = 4.3$ m/s. ΔL is 0.8 mm in (a) and 1.6 mm in (b).



(a) (b) (c)

Fig. 5. Deformation behavior of two droplets impacting successively onto a solid surface at room temperature with $d_{p1} = 0.57$ mm, $d_{p2} = 0.39$ mm, $v_1 = 2.3$ m/s, $v_2 = 2.4$ m/s. ΔL is 0.8, 1.25 and 1.55 mm for (a), (b) and (c), respectively.

Fig. 5 represents the collision of two successive droplets with a solid at room temperature with $d_{p1} = 0.57$ mm, $d_{p2} = 0.39$ mm, $v_1 = 2.3$ m/s and $v_2 = 2.4$ m/s ($We_1 = 41$, $We_2 = 30$). The spacing, ΔL, is 0.8, 1.25 and 1.55 mm for (a), (b) and (c), respectively. The inertia of the droplets, particularly the second(trailing) one, is small compared to the previous case shown in Fig. 4 which suggests that there is less driving force for the formation of the liquid swelling. The coalesced liquid deforms into the shape of a crown at $\tau = 2.7$, 3.1 and 3.6 for cases (a), (b) and (c), respectively, with heights lower than those in Fig. 4. The liquid crown then falls radially outward, followed by a reverse flow from the edge to the center due to the effects of surface tension. The liquid in the edge part moves inward which leads to liquid swelling ($\tau = 4.7$ (a), 5.0 (b), 5.4 (c)). Eventually, the coalesced liquid settles into a convex-lens shape.

3.2. Collision of water droplets with a hot solid at 300 °C

Fig. 6 depicts a sequence of photographs showing the collision of a single droplet with a hot solid at 300 °C with $d_p = 0.59$ mm, $v = 3.95$ m/s ($We = 124$) for case (a) and $d_p = 0.54$ mm, $v = 3.0$ m/s ($We = 72$) for case (b). In case (a), the droplet impacts on the solid and then deforms into a circular thin disk ($\tau = 1.2$). Many small secondary droplets appear above the body of the liquid. The liquid first breaks up into many small parts and then disintegrates into small droplets moving radially outward. At $\tau = 6.5$, the liquid pieces are no longer attached to the solid.

The deformation mechanism of droplet is explained as follows: Before the impact, the droplet is heated by thermal radiation from the hot solid as it approaches the solid substrate. However, the radiation heat transfer is negligibly small and the amount of vaporization on the wall-facing side of the droplet is not enough to prevent direct contact between the droplet and the hot solid. Upon contact, the temperature difference between the liquid and the solid leads to a high degree of convective heat transfer. The temperature of the solid surface in contact with the liquid decreases temporarily as well as locally while the liquid near the solid surface is being heated. The formation of vapor bubbles arises at the liquid/solid interface due to boiling. The vapor bubbles detach from the solid surface, ascend in the liquid owing to the buoyancy force, and finally release to the atmosphere. Such bubble motion results in the formation of numerous secondary droplets above the body of liquid and promotes the disintegration of droplet. Since the disintegration of droplets occurs during the spreading process, the small droplets move radially outward. The solid surface is reheated owing to heat conduction from the inner material and additional vapor is generated in the solid/liquid region. Eventually, all small liquid mass will detach from the solid and convective heat transfer due to contact of the liquid with the solid surface will cease.

In case (b) with $We = 72$, the collision behavior displays a similar trend. The droplet impact inertia is reduced which results in a smaller droplet spread. Secondary droplets above the body of liquid due to boiling can still be seen as in case (a) with $We = 124$, but to a lesser extent.

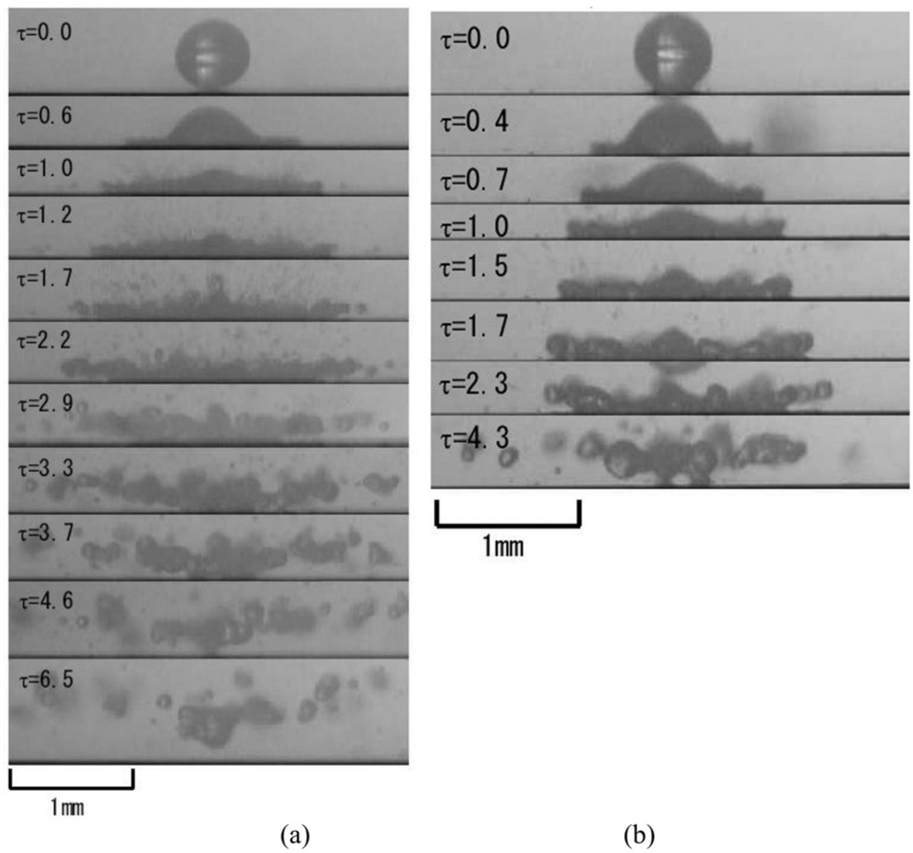


Fig. 6. Deformation behavior of a single droplet impacting onto a hot solid surface at 300 °C (a) $d_p = 0.59$ mm, $v = 3.95$ m/s, (b) $d_p = 0.54$ mm, $v = 3.0$ m/s.

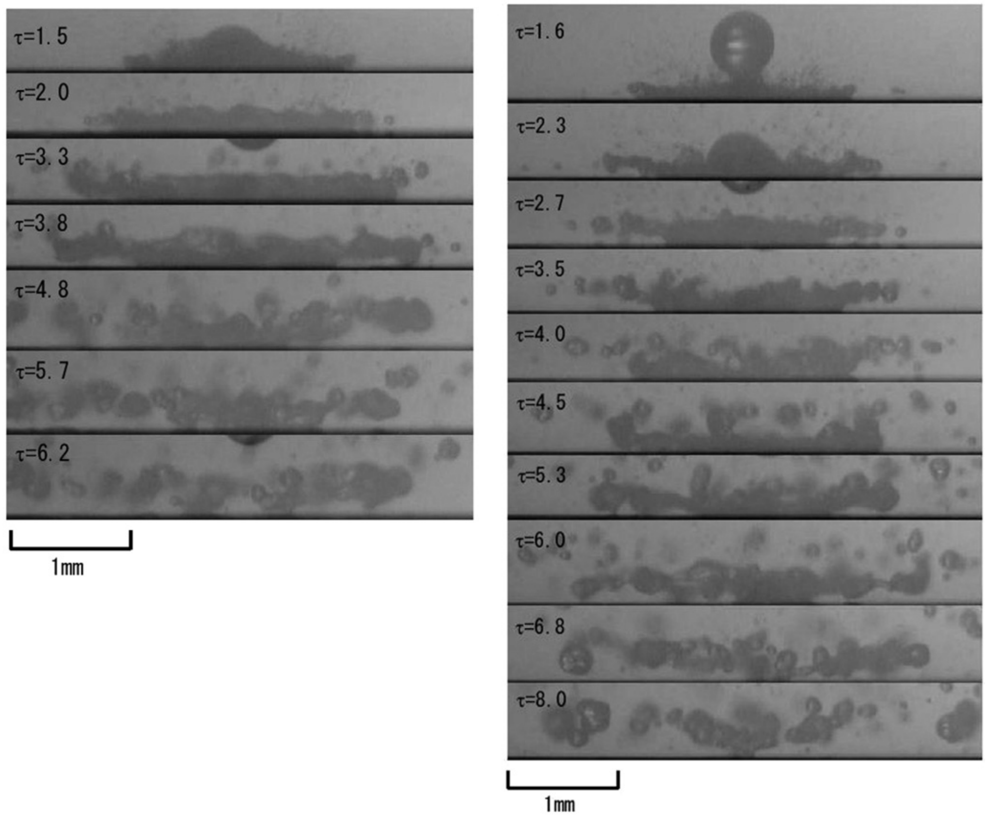
Fig. 7 shows the results of the collision of two successive droplets onto a hot solid with $d_{p1} = 0.60$ mm, $d_{p2} = 0.60$ mm, $v_1 = 3.95$ m/s and $v_2 = 4.0$ m/s ($We_1 = 127$, $We_2 = 130$). The spacing, ΔL, is 0.7 and 1.1 mm for (a) and (b), respectively. In both cases, numerous secondary droplets have already been jetted from the body of the first droplet (see also Fig. 6(a)) when the second droplet arrives at the top of the first droplet. The free surface of first droplet is believed to be greatly distorted or might even be partially disintegrated by the presence of vapor bubbles. Thus, the pressure distribution near the impact point becomes essentially three-dimensional. The inertia of the second droplet dissipates randomly in all directions. As a consequence, the formation of crown does not occur. The duration for which the liquid appear to be in contact with the solid surface is longer than that in the case of a single droplet. Eventually, the liquid breaks up into many smaller droplets which move radially outward.

Fig. 8 depicts the deformation behavior of two droplets with $d_{p1} = 0.54$ mm, $d_{p2} = 0.54$ mm, $v_1 = 3.0$ m/s, $v_2 = 3.1$ m/s ($We_1 = 66$, $We_2 = 70$), and $\Delta L = 0.7$ mm. The impact condition for the first droplet is the same as that in Fig. 6(b). Liquid film observed from the side-view photos is thicker than that of the single droplet case because the volume of liquid is double. At the instant when the second droplet arrives ($\tau = 0.9$), the first droplet is in the process of spreading on the solid surface. The coalesced liquid continues to spread. Incidentally, since heat transfer from the solid to the liquid increases with liquid/solid contact area, the heat transfer rate is larger than that for a single droplet collision.

Fig. 9 demonstrates the successive collision of two droplets on a hot solid with $d_{p1} = 0.64$ mm, $d_{p2} = 0.64$ mm, $v_1 = 2.45$ m/s and $v_2 = 2.55$ m/s ($We_1 = 52$, $We_2 = 56$). The spacing between the two droplets, ΔL, is 1.15 and 1.55 mm for (a) and (b) respectively. At the instant when the second droplet arrives, the first droplet has deformed into a thin disk on the solid with some isolated liquid masses detached from the main body. The height of the coalesced liquid at the center axis decreases with time, while the diameter of liquid remains almost constant. Thereafter, a large portion of the liquid moves to the edge region. The coalesced liquid appears as a distorted crown with a thin liquid film around the center axis and several thick liquid masses in the edge regions in addition to several isolated small droplets away from the main body of liquid. No appreciable effects of ΔL on the collision behavior can be seen.

3.3. Collision of water droplets with a hot solid at 500 °C

Fig. 10 depicts the deformation behavior of (a) a single droplet and (b) two successive droplets impinging onto a hot solid at 500 °C. The impact conditions are (a) $d_p = 0.64$ mm, $v = 2.35$ m/s ($We_1 = 48$), (b) $d_{p1} = 0.64$ mm, $d_{p2} = 0.64$ mm, $v_1 = 2.35$ m/s, $v_2 = 2.45$ m/s ($We_1 = 48$ and $We_2 = 52$), and $\Delta L = 1.35$ mm. In case (a), the droplet impinges on the solid, spreads radially, deforms into a thin disk. The leading edge of thin liquid film is rounded. The pressure in the leading edge



(a) (b)

Fig. 7. Deformation behavior of two droplets impacting successively onto a hot solid surface at 300 °C with $d_{p1} = 0.60$ mm, $d_{p2} = 0.60$ mm, $v_1 = 3.95$ m/s, $v_2 = 4.0$ m/s. $\Delta L = 0.7$ and 1.1 mm for (a) and (b), respectively.

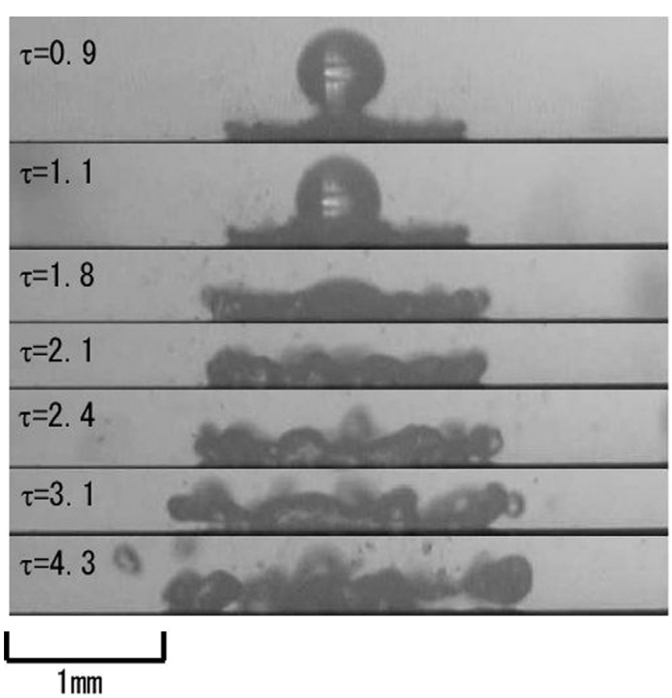
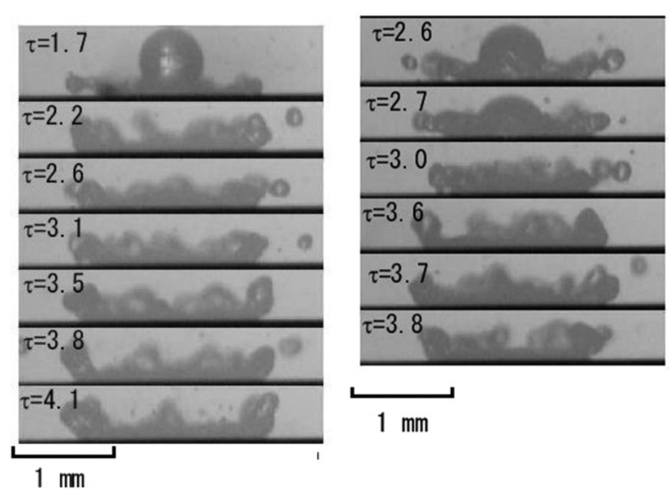


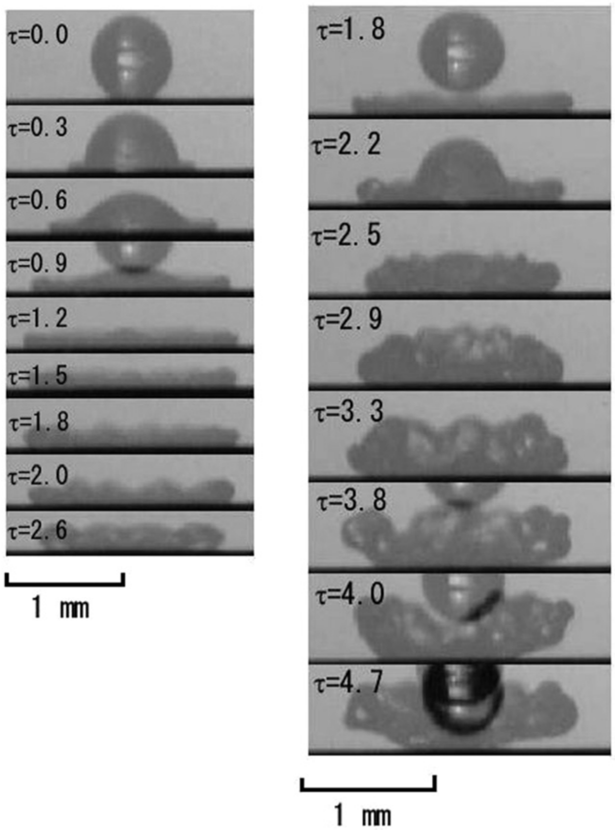
Fig. 8. Deformation behavior of two droplets impacting successively onto a hot solid surface at 300 °C with $d_{p1} = 0.54$ mm, $d_{p2} = 0.54$ mm, $v_1 = 3.0$ m/s, $v_2 = 3.1$ m/s and $\Delta L = 0.7$ mm.



(a) (b)

Fig. 9. Deformation behavior of two droplets impacting successively onto a hot solid surface at 300 °C for $d_{p1} = 0.64$ mm, $d_{p2} = 0.64$ mm, $v_1 = 2.45$ m/s, $v_2 = 2.55$ m/s. $\Delta L = 1.15$ and 1.55 mm for (a) and (b), respectively.

must be relatively high due to surface tension. This results in a reverse flow from the edge to the center. As a consequence, the droplet recoils. The disintegration of droplets does not occur because of small Weber number [4]. The formation of small secondary droplets previously observed above the body of liquid due to vapor bubbles is not noticeable in the figure. This



(a) (b)

Fig. 10. Deformation behavior of (a) a single droplet and (b) two successive droplets impacting onto a hot solid surface at 500 °C. (a) $d_p = 0.64$ mm, $v = 2.35$ m/s, (b) $d_{p1} = 0.64$ mm, $d_{p2} = 0.64$ mm, $v_1 = 2.35$ m/s, $v_2 = 2.45$ m/s, and $\Delta L = 1.35$ mm.

suggests that a thin vapor film might be formed between the liquid and the solid surface and the liquid is isolated from the solid surface because of higher surface temperature.

In the case of successive collision, the second droplet impacts onto the first droplet at $\tau \sim 1.8$ when the first droplet is on the verge of reaching the maximum diameter and about to begin the recoiling process. The spreading edge of the first droplet reduces with time ($\tau = 1.8$, 2.2) because of the surface tension effect as previously mentioned. More specifically, the radially inward flow arises in the edge part of the liquid. On the other hand, the height of the coalesced liquid at the center decreases monotonically with time due to the inertia of the second droplet, resulting in a radially outward flow from the center. After $\tau = 2.9$, the coalesced liquid is in the shape of a distorted crown.

4. Conclusions

The deformation behavior of two water droplets impinging successively onto a cold or hot solid surface was studied by means of photography. The effect of surface temperature, impact inertia and the spacing between the two droplets on the deformation behavior of liquid was investigated. The findings obtained in the present study are summarized as follows:

(1) The formation of a liquid crown is clearly observed at room temperature. The height of the crown is larger with wider spacing between two droplets and higher droplet impact inertia (Weber number).
(2) For the case of 300 °C, the boiling of liquid occurs at the solid–liquid interface, resulting in numerous secondary droplets appearing above the deformed droplet. For a relatively large *We* number, the droplet splits into pieces and a liquid crown cannot be seen.
(3) A crown is also seen at high surface temperatures for small *We* numbers, although it is considerably distorted.

Acknowledgements

This research was supported by Grant-in-Aid for scientific research (c) (#16560185) provided by Japan Society for the Promotion of Science and by the ISIJ research promotion grant.

References

[1] B.R. Holt, A.Y. Tong, Numerical simulation of a liquid metal droplet impacting onto a rigid substrate, in: 4th ASME/JSME Thermal Engineering Joint Conference, Hawaii, vol. 2, 1995, pp. 149–156.
[2] A.Y. Tong, B.R. Holt, A numerical study on the solidification of liquid droplets impacting onto a substrate, Numerical Heat Transfer Journal Part A: Applications 31 (1997) 797–817.
[3] M. Rein, Phenomena of liquid drop impact on solid and liquid surfaces, Fluid Dynamics Research 12 (1993) 61–93.
[4] N. Hatta, H. Fujimoto, H. Takuda, K. Kinoshita, O. Takahashi, Collision dynamics of a water droplet impinging on a rigid surface above the Leidenfrost temperature, ISIJ International 35 (1995) 50–55.
[5] M. Bussmann, J. Mostaghimi, S. Chandra, Modeling the splash of a droplet impacting a solid surface, Physics of Fluids 12 (2000) 3121–3132.
[6] N. Hatta, H. Fujimoto, K. Kinoshita, H. Takuda, Experimental study of deformation mechanism of a water droplet impinging on hot metallic surfaces above the Leidenfrost temperature, Transactions of the ASME Journal of Fluids Engineering 119 (1997) 692–699.
[7] J. Fukai, Y. Shiiba, T. Yamamoto, O. Miyatake, D. Poulikakos, C.M. Megaridis, Z. Zhao, Wetting effects on the spreading of a liquid droplet colliding with a flat surface: experimental and modeling, Physics of Fluids 7 (1995) 236–247.
[8] A.L. Yarin, Drop impact dynamics, Annual Review of Fluid Mechanics 38 (2006) 159–192.
[9] A.L. Yarin, D.A. Weiss, Impact of drops on solid surfaces: self-similar capillary waves, and splashing as a new type of kinematic discontinuity, Journal of Fluid Mechanics 283 (1995) 141–173.
[10] H. Fujimoto, T. Ogino, H. Takuda, N. Hatta, Collision of a droplet with a hemispherical static droplet on a solid, International Journal of Multiphase Flow 27 (2001) 1227–1245.
[11] H. Fujimoto, T. Ogino, N. Hatta, H. Takuda, Numerical simulation of successive collision of two liquid droplets with a solid wall, ISIJ International 41 (2001) 454–459.
[12] H. Fujimoto, S. Ito, I. Takezaki, Experimental study of successive collision of two water droplets with a solid, Experiments in Fluids 33 (2002) 500–502.
[13] H. Fujimoto, I. Takezaki, Y. Shiotani, A.Y. Tong, H. Takuda, Collision dynamics of two droplets impinging successively onto a hot solid, ISIJ International 44 (2004) 1049–1056.
[14] A. Karl, A. Frohn, Experimental investigation of interaction processes between droplets and hot walls, Physics of Fluids 12 (4) (2000) 785–796.
[15] A.Y. Tong, S. Kasliwal, H. Fujimoto, On the successive impingement of droplets onto a substrate, Numerical Heat Transfer Journal Part A: Applications, in press.