Experimental study on two consecutive droplets impacting onto an inclined solid surface
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ABSTRACT

The present study is concerned with the experimental impingement of two consecutive droplets on an inclined solid surface. Attention is mainly paid to the effects of impingement timing with various oblique angles (Φ) of the surface on the impact phenomena, which mainly affect the maximum droplet spreading diameter. The investigation considers four impingement scenarios differentiated by impingement timing, namely Case 1: single-droplet impingement; Case 2 of Δt1: the moment when the leading droplet starts spreading along the oblique surface; Case 3 of Δt2: the moment when the leading droplet reaches its maximum spreading; and Case 4 of Δt3: the moment when the leading droplet starts retracting. It is observed that deformation behavior of two successive droplets impacting on the inclined surface experiences a complex asymmetric morphology evolution due to the enhancement of gravity effect and various conditions of the impingement timing. The merged droplet becomes slender with increasing oblique surface angle in the final steady shape, causing the decrease in the value of front and back contact angles. The impingement timing has a significant influence on the change of the maximum height of the merged droplet. The coalesced droplet spreads to the maximum dimensionless width diameter at Δt = Δt2 and the oblique angle of Φ = 45°, but reaches the maximum dimensionless height for Δt = Δt3 at Φ = 30°. The front contact angles converge to a fixed value eventually for all conditions of impingement timing, and the values become lower with the increasing surface inclination.

KEYWORDS: inclined solid surface, Weber number, oblique angle, impingement timing

1. INTRODUCTION

It has been well known that a liquid droplet impinging on a solid surface can be found ubiquitously in nature. Understanding the phenomenon is increasingly important for a variety of industrial applications such as spray coating [1], atomizer [2], power engineering [3], agriculture [4], forensic science [5] and so on. More than one century of continuing efforts, the mechanisms are still far from being completely elucidated [6]. By properly understanding the impingement behavior, characteristics of the droplet spreading behavior, droplet heat transfer and satellite droplet formation are essential in optimizing the system performance for spray cooling and inkjet printing applications. Similarly, a knowledge of the splashing or spreading of blood impacting on a surface can yield valuable clues regarding the details of a crime scene in criminal investigations.

In the past decades, a considerable amount of work has been devoted to the classical phenomenon for impingement and liquid–solid interface of single or multiple droplets on horizontal surfaces, theoretically [7, 8], experimentally [9, 10] and numerically [11–14]. Additionally, comprehensive reviews of this subject are available to study the historical development and deformation evolution mechanism (e.g. [15–17]). The deformation behavior of the droplet impinging on the surface is influenced by major influencing parameters [18, 19], including the working fluid, droplet size, impact velocity, surface property, the impact direction with respect to the surface, wall temperature, etc. On the other hand, many practical engineering applications in reality require a fundamental understanding of the droplet impact behaviors on surfaces at a variety of inclined angles, such as impingement of rain droplets on the windshield or airplane wings, impact of condensed droplets on turbine blades and effect of fuel injection on the internal wall surface of the combustor [20, 21]. From an extensive literature survey, it is found that relatively less attention is paid to the droplet impact on the inclined wall. Apart from the axisymmetric morphology evolution on horizontal solid surfaces, the presence of surface inclination causes the droplet to experience an
asymmetrical behavior along the tilted wall, which makes the deformation mechanism far more complex. When the droplet impinges on the solid obliquely, such collision outcome is attributed to the coupling effects from the impact inertia, gravity, surface tension and viscous forces, leading to more complicated deformation phenomena than those of impacting vertically onto a horizontal plate.

In the literature, just the same as the impingement on flat surfaces, a number of studies, such as those by the research groups of Fujimoto [22, 23] and Šikalo [24–26], have been performed with the case of only a single droplet impacting onto a tilted surface in order to simplify the problem and to highlight relevant mechanisms. Only a few studies have been devoted toward two-droplet collisions with oblique solid surfaces. Antonini et al. [27] investigated the oblique impact of water droplets on hydrophobic and superhydrophobic surfaces to focus on the droplet impinging dynamics and the conditions for droplet rebound on low wetting surfaces. The surface inclination facilitated droplet rebound from the superhydrophobic surface. For droplet impact on a hydrophobic surface, increasing surface inclination and impact Weber number led to a transition from droplet rebound to partial rebound and sliding, and finally to rivulet. Fujimoto et al. [28] studied experimentally the successive impingement of two liquid droplets obliquely on a hot solid surface. The effects of the spacing between the two droplets and their impact angle on the surface were studied at a temperature of 500°C. The overall liquid motion presented linearly symmetric deformation, and rebounding was also observed, affected by the spacing between the leading and trailing droplets. Raman et al. [29] investigated the interaction dynamics between two droplets impinging simultaneously on the dry surface by numerical simulations. The effect of droplet impact angle on the interaction dynamics was further studied and larger overlapping between two droplets was found with the increasing impact angle. Guo and Lian [30] used numerical simulations to investigate the oblique impact of two adjacent droplets on a thin liquid layer for low-speed and high-speed impacts. Also, Ahmad et al. [31] conducted a numerical work to study the oblique impact of two successive droplets on a flat surface. The effects of impact obliqueness and lateral/longitudinal offset on the subsequent dynamics of the combined droplet were discussed. The lattice Boltzmann method is a good scheme to simulate the complicated fluid–fluid and fluid–surface interactions [32].

From the above review of previous studies, the experimental research focusing on the two successive droplets impacting on the oblique surface is rather limited and the effects of the impingement timing of two successive droplets on the deformation behaviors are not investigated in detail, especially in the case of the inclined surface. Different from previous studies of the impingement behavior of two droplets impacting on an inclined surface in succession, the present work performs an experimental investigation with focus on the effect of the impingement timing of the leading droplet deformation. Then, a detailed analysis of the coalesced droplet diameter and height is done for further understanding the complex morphology evolution. Finally, contact angles at the front and the tail of the droplets on the solid surface are measured to describe the droplet impact process.

2. EXPERIMENTAL SETUP AND MEASUREMENT

The aim of the experiment is to investigate two identical droplets successively impacting onto inclined surfaces with various oblique angles (φ) of 15°, 30° and 45°. Pure water at room temperature of 25°C is employed as the working fluid with a density of 995.2 kg/m³ and surface tension of 71.2 × 10⁻² N/m. The initial diameter of spherical droplets is set to 930 ± 15 μm.

2.1 Experimental setup

In the present study, the experimental setup, which comprises a droplet generator system, an impinging plate system and an image acquisition system, is shown in Fig. 1 for the droplet impingement. The droplet stream generation system consisted of a water reservoir, a droplet generator, a function generator and a droplet severance system. The reservoir was installed to supply a steady pressure and needle valves were used to control liquid volume flow rates into the droplet generator. A series of droplets were issued through the glass needle under the effects of a piezoelectric plate actuated by the function generator that controlled the frequency and the amplitude of droplet generation. The frequency component of the function generator was used for adjusting the space between the droplets in the droplet stream, and the amplitude component was used to maintain the shape and stability of the droplet stream. The droplet severance device was equipped with a rotating disk segregating the continuous droplet stream into discrete groups of two droplets with the required impingement timing.

The impinged plate system consisted simply of a stainless steel plate, a temperature controller and a stage platform designed to adjust the oblique angle of the plate with respect to the incoming droplets and the distance between the steel surface and the disk severance system, respectively. The droplet impact surface was a polished stainless steel plate with a roughness of Ra = 0.055 μm, the smooth class between a polished aluminum (Ra = 0.147 μm) and a glass (Ra = 0.015 μm), and was kept at the ambient temperature of 25°C. A stroboscope, a high-speed camera and a halogen lamp were adopted in the visualization method to record the impinging behavior quantitatively. The stroboscope was synchronized with the frequency of the

![Figure 1 Schematic representation of the experimental setup.](https://academic.oup.com/jom/article-lookup/doi/10.1093/jom/ufab012/6297654)
function generator and was aligned toward the high-speed camera. During the droplet impingement experiment, the droplet stream and impinging plate were illuminated by the halogen lamp. Experimental images of the impact dynamics were captured by the camera at rates of up to 100 000 fps and recorded into a computer for further pixel-based analysis. The initial diameter ($d_i$) of a droplet is measured from these images using commercial image processing software (ImageJ) and can be estimated as

$$d_i = (d_h d_w)^{1/3},$$  \hspace{1cm} (1)

where $d_h$ and $d_w$ are the droplet height and the droplet width, respectively.

The definitions applied in measuring $d_h$, $d_w$, front contact angle ($\theta_{\text{front}}$) and back contact angle ($\theta_{\text{back}}$) between droplets and an oblique solid surface are presented in Fig. 2. The velocity of the droplets is measured using the frequency of the droplet generator ($f$) and the spacing ($s$) between the droplets on the images, namely

$$V = fs.$$  \hspace{1cm} (2)

Conventionally, the Weber number ($We$) is an important factor dictating the deformation behavior of the droplet impact on the solid surface and it is defined as the ratio of droplet inertia to droplet surface tension force, which can be determined as follows:

$$We = \frac{\rho V^2 d_i}{\sigma},$$  \hspace{1cm} (3)

where $\rho$ is the density and $\sigma$ is the surface tension.

For a very low Weber number impact, if the inertia force cannot overcome the surface tension force, the droplet may stick to the surface. As the Weber number increases, the inertia becomes much greater than the surface tension and the droplet impact behavior changes from the sticking to the spreading regime. At a further larger Weber number, the splashing regime prevails because of the high impact energy. In the present work, all of the impingement cases are classified as low Weber number impingement ($We = 40–50$), which is in the spreading regime.

### 2.2 Droplet spacing parameter ($\Delta t$)

Figure 3 sketches schematic representations for the three impingement conditions for an oblique impact surface. For Case 2 of $\Delta t = \Delta t_1$, the leading droplet moves downward vertically to impinge the oblique plate and just starts to spread along the oblique surface at that very time the trailing droplet impacts the leading one. In Case 3, $\Delta t = \Delta t_2$, the trailing droplet impinges on the leading droplet at the moment it reaches its point of maximum spreading diameter. Finally, for Case 4 of $\Delta t = \Delta t_3$, the leading droplet is impinged by the trailing droplet as it starts to contract. As shown in Table 1, the droplet impingement tests were carried out using three different time intervals to identify the deformation behavior of the leading droplet. The oblique angle of the solid surface is set as $\Phi = 15^\circ$, $30^\circ$ and $45^\circ$, respectively.

### 2.3 Photography and experimental procedure

The working fluid was issued through the droplet generator from a high-positioned reservoir that provides a stable rate of water supply. The function generator signals with the frequency required to achieve the droplet spacing parameters were sent to the droplet generator to control droplet generation. Ensuring a stable stream of spherical droplets, the amplitude of the input signal was adjusted for each set of experimental conditions. Additionally, the frequency of the stroboscope was usually synchronized with the droplet-generating frequency in order to freeze the droplet stream for taking a clear picture. The droplet severance system was used to divide the droplet stream into groups of two droplets, which subsequently impinged on the oblique surface. Visualization for the recording of the impinging behavior was achieved by using a high-speed camera. Each experimental procedure was independently repeated at least three times to assess the reproducibility and reliability. Moreover, the stainless steel surface was not only cleaned between each group of two droplets to minimize the effects of surface impurities on the droplet impingement but also prepared by polishing to reduce the influence of surface roughness on the impact. Finally, the droplet size including initial diameter, droplet height and

![Figure 2 Definitions of the dimensions used to measure the droplet width ($d_w$), droplet height ($d_i$), front contact angle ($\theta_{\text{front}}$) and back contact angle ($\theta_{\text{back}}$) for (a) a single droplet and (b) a coalesced droplet.](https://academic.oup.com/jom/article/doi/10.1093/jom/ufab012/6297654)
droplet width, impact velocity, droplet spacing, front contact angle and back contact angle were measured from video pictures using ImageJ software as a tool for morphometric analysis. The detailed statement of the method for uncertainty analysis in this experiment was provided in our previous work [33]. A summary of uncertainty is presented in the following discussion. The imaging parallax includes an uncertainty corresponding to one pixel or 4% for the estimation of the droplet size, i.e. diameter, height and width. The errors of droplet velocity and deformation time measurement, respectively, are within 2% and 3%. The angle of surface inclination is measured with the accuracy of 1%.

3. RESULTS AND DISCUSSION

Figures 4–7 show the experimental results obtained for the single-droplet and two-droplet impacts on solid surfaces with oblique angles of $\Phi = 15^\circ$, $30^\circ$ and $45^\circ$, respectively. Note that the contours are presented with a horizontal direction, while the spreading direction is from right to left.

3.1 Variation in droplet shape

At first, the impingement morphology of a single droplet was examined as a reference and compared with other cases to assess differences and similarities. Figure 4 addresses the time evolution of the impingement of a single droplet on the inclined surface with various conditions of oblique angles: (a) $\Phi = 15^\circ$, (b) $\Phi = 30^\circ$ and (c) $\Phi = 45^\circ$. A sequence of images of the impact event showing the collision behavior are explored. It is seen in Fig. 4a that after impacting on the inclined plate with $\Phi = 15^\circ$, the droplet initially deposits on the surface, spreads along the surface with a reducing thickness and undergoes a flattening effect until $t = 0.7$ ms due to the effect of gravity and inertia, leading to the maximum spreading diameter at around $t = 1.2$ ms. Because of surface tension and viscous forces, the left part of the droplet starts accumulating before the spreading diameter contracts from left to right. The droplet presents an asymmetry change after $t = 1.2$ ms since the solid surface is inclined. Before the spreading diameter stabilizes, it repeats a contracting change. Eventually, the droplet arrives at the final equilibrium state in the shape of truncated sphere stemming from the energy dissipation.

With an increase in the oblique angle, as the case of $\Phi = 30^\circ$ in Fig. 4b, the evolution of the droplet contour before $t = 0.7$ ms is similar to that of an oblique angle of $\Phi = 15^\circ$. However, the back edge of the droplet moves downward slowly along the surface and stretches out toward the superlative level of the maximum spreading at $t = 1.5$ ms. Subsequently, the surface tension-driven retraction occurs and the front end of the droplet begins to recoil over the interval of $t = 2.5–3.8$ ms by forming in the shape of a bulge with a long and thin tail, causing the droplet to become slender. Eventually, the swelling part of the droplet shifts left and right reciprocally and then stabilizes.

For a further larger oblique angle $\Phi = 45^\circ$ as shown in Fig. 4c, the droplet spreads on the inclined plate due to gravity-driven flows and the deformation in the shape of the droplet has a tendency similar to those of $\Phi = 15^\circ$ and $\Phi = 30^\circ$ prior to $t = 0.7$ ms. Afterward, asymmetrical behavior gives the trend resembling the case of $\Phi = 30^\circ$ from $t = 1.6$ to $3.9$ ms. It is quite different from other two oblique angles that the maximum spreading diameter occurs at $t = 3.9$ ms after irregular morphology. The inward liquid then moves from left to right until it reaches a state of equilibrium in an elongated shape. Notably, compared to the results of $\Phi = 15^\circ$ and $\Phi = 30^\circ$, it is seen that the final geometric structure in steady shape on a surface with the greatest oblique angle of $\Phi = 45^\circ$ is far slenderer.

The results shown in Fig. 4 address the effect of the gravity on the deformation behavior. After impacting the surface, the droplet is affected by the gravitational force normal to the wall, causing the increase in the spreading and remarkable accumulation at the front end of the droplet in the spreading phase [34]. During the retracting stage, the gravity tangential to the wall alleviates the droplet retraction. The droplet shape in the final steady state becomes more slender due to the enhancement of the gravity. Moreover, the gravity effect becomes more profound with increasing surface slope.

For the two similar-sized droplets impinging on the inclined plate for Case 2 of $\Delta t_1$ with various oblique angles, (a) $\Phi = 15^\circ$, (b) $\Phi = 30^\circ$ and (c) $\Phi = 45^\circ$ in Fig. 5, the trailing droplet collides with the leading droplet just after the leading one hits the solid surface and starts to spread along the oblique surface. Compared to single-droplet impact, a pair of droplets impacting on an oblique surface in succession shows quite different dynamics because of the involved coalescence. At a tilt angle of $\Phi = 15^\circ$ for $\Delta t_1 = 0.6$ ms shown in Fig. 5a, the second droplet interacts and coalesces with the first one after collision, and the combined droplet becomes asymmetric. The rear end of the droplet has the form of a thin film in which the upper region is wider than the bottom at $t = 1$ ms since the internal flow near the wall is affected by friction forces from the solid surface. As time goes on, the thin liquid film starts to move from right to left.
resulting from the combined effect of the inertia force and gravity. At \( t = 2 \text{ ms} \), the left part of the droplet starts accumulating and the central region of the film swells up due to surface tension at \( t = 2.6 \text{ ms} \). The merged droplet continues to move from left to right, and gradually approaches the final steady state.

For the tilt angle of the surface, \( \Phi = 30^\circ \), in the case of \( \Delta t_1 = 0.6 \text{ ms} \), the thin spreading film is relatively wider at the upper surface of the left-hand portion than lower surface at \( t = 1.3 \text{ ms} \) presented in Fig. 5b. A thin film with a peak at the front edge of the droplet can be observed at \( t = 1.6 \text{ ms} \) stemming from a higher surface oblique angle, and the film height increases to a maximum value at \( t = 1.8 \text{ ms} \). Thereafter, the left portion of the droplet accumulates on the left side until \( t = 4.3 \text{ ms} \), at which point the droplet starts to retract back toward the upstream side before the final steady-state equilibrium is reached.

With the tilt angle further increasing, e.g. the case of \( \Phi = 45^\circ \) for \( \Delta t_1 = 0.5 \text{ ms} \) (see Fig. 5c), the droplet is stretched with a relatively wider film at the upper left as compared to that at the lower right at \( t = 1.4 \text{ ms} \). After this point, the downstream region of the film starts swelling and becomes a thumb-shaped edge and the maximum film height occurs at an elapsed time of \( t = 2.1 \text{ ms} \). Afterward, the left part of the droplet undergoes accumulation until \( t = 3.7 \text{ ms} \) and then starts contracting from left to right. The contour changes into eyebrow shapes to reach the equilibrium

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**Figure 4** Time evolution of single droplet impinging on the inclined surface with various conditions of oblique angles: (a) \( \Phi = 15^\circ \), (b) \( \Phi = 30^\circ \) and (c) \( \Phi = 45^\circ \).
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Figure 5 Time evolution of two successive droplets impinging on the inclined surface for Case 2: $\Delta t = \Delta t_1$ with various conditions of oblique angles: (a) $\Phi = 15^\circ$, (b) $\Phi = 30^\circ$ and (c) $\Phi = 45^\circ$.

State eventually. As for the single-droplet event, the final droplet configuration with an oblique angle of $\Phi = 45^\circ$ is more slender than those of $\Phi = 15^\circ$ and $30^\circ$ since the gravity becomes more pronounced as the inclined angle of solid surfaces increases.

In Case 3 of $\Delta t_2$ as shown in Fig. 6, the trailing droplet impinges on the leading droplet at the time the leading one reaches the maximum extent of spreading. For the inclined angle of $\Phi = 15^\circ$ and $\Delta t_2 = 1.1$ ms in Fig. 6a, the trailing droplet compresses the leading droplet and the liquid swells up resulting in the undulate shape at $t = 1.5$ ms. The inward fluid is accumulated obviously at the front edge caused by gravity forces and impact inertia from $t = 1.8$ to 2.1 ms and the leading-edge side of the droplet reaches a maximum height at $t = 2.3$ ms as time progresses. Thereafter, the merged droplet starts to retract back due to the surface tension force, driving the liquid to flow inward approaching the droplet center at $t = 3.4$ ms. Again, the gravity component tangential to the solid surface enhances the accumulation of the fluid at the front edge until $t = 3.9$ ms, at which point it begins to recede back from left to right. Over time, the coalesced droplet reaches an equilibrium condition in the shape of oblate spheroid.

As the inclined angle increases to $\Phi = 30^\circ$ for Case 3 of $\Delta t_2 = 1.2$ ms in Fig. 6b, the advancing side of the liquid film swells, leading to a highlighted region of the peak near the front portion of the droplet, and the film reaches its maximum height at $t = 2.8$ ms. Thereafter, the apparent peak is
obviously weakened and shifts toward the rearward part during the time interval of $t = 3.3$–$3.8$ ms. Finally, the left part of the droplet accumulates and exhibits a recession process until the droplet stabilizes. At further higher inclined angle, $\Phi = 45^\circ$, the deformation sequence in Fig. 6c is similar to the behaviors of the case with $\Phi = 30^\circ$. However, a longer time is taken for the thin film to accumulate, migrating away from the front side of the droplet bulk, and an extremely slender shape is formed in the final equilibrium state due to the enhancement of gravity.

Figure 7 presents a series of experimental images of two droplets in tandem impacting on the inclined surface with various oblique angles, i.e. $\Phi = 15^\circ, 30^\circ$ and $45^\circ$ for Case 4 of $\Delta t_3$, the trailing droplet impinging on the leading droplet at the moment. When the leading droplet forms a peak in the front region to start retracting. During time evolution of two successive droplets impinging on a solid surface with slanted surfaces, $\Phi = 15^\circ$, for $\Delta t_3 = 2.5$ ms as shown in Fig. 7a, the collision of the trailing droplet forces the leading droplet to move further in the leftward direction, causing accumulation of the droplet liquid on the front side by $t = 3.1$ ms. Next, the left part of the coalesced droplet begins accumulating and then contracts retracting back from the edges until around $t = 4.2$ ms. Consequently, the droplet continues to move from left to right prior to final stabilization.
Further increasing the tilted angle, i.e. $\Phi = 30^\circ$, for $\Delta t_1 = 2.4$ ms as seen in Fig. 7b, the trailing droplet impinges on the leading droplet that has previously accumulated. With a momentum component in the tangential direction along the surface, the trailing droplet coalesces with the first one, producing the forward movement to form a liquid protrusion on the front spreading side from $t = 2.6$ to 3.4 ms. Hereafter, the kinematic energy is changed into surface tension energy, leading the contraction from left to right up to $t = 4.7$ ms, and continues to vary until the droplet reaches its final equilibrium. As the oblique angle further increases up to $\Phi = 45^\circ$ (see Fig. 7c), the deformation evolution becomes more evident and the droplet shifts gradually forward with a long tail. Then, the merged droplet turns into a slender shape as a consequence of gravity, inertia, viscosity and surface tension. Compared to the results presented in Fig. 7a and b, the final steady-state equilibrium shape with 45° tilting angle is the most slender since the gravitational force becomes more influential.

### 3.2 Variation in spreading diameter and vertical height

Figure 8 illustrates the variation of dimensionless width diameters ($d_w^* = d_w/d_i$) of the droplet at four impingement conditions (i.e. single, $\Delta t_1$, $\Delta t_2$ and $\Delta t_3$) over dimensionless
time ($t^* = tV/d_0$) with three different surface oblique angles such as $\Phi = 15^\circ$, $30^\circ$ and $45^\circ$. Unlike a horizontal surface ($\Phi = 0^\circ$), the nondimensional maximum spreading diameter ($d_{w,\text{max}}^*$) of droplets impacting on the tilting surface is much lower since the droplet suffers a gravity component tangential to the surface, causing an asymmetric spreading of the droplet, and in turn the $d_{w,\text{max}}^*$ is reduced. During very early period of the impingement, the spreading diameter of two successive droplets impacting on three surface inclinations has an identical ascending trend similar to that of the single droplet.

The single droplet exhibits the maximum value of $d_{w,\text{max}}^* = 2.28$ at $t^* = 2.4$ for $\Phi = 15^\circ$, after which it is interestingly observed to have rapidly reduced due to the surface force, recoiling flow from the front end of the droplet, and followed a constant trend thereafter as shown in Fig. 8a. As the surface angle increases to $\Phi = 30^\circ$, $d_{w,\text{max}}^*$ reaches the maximum level of 2.66 at $t^* = 2.86$, which is larger than that of $\Phi = 15^\circ$, because of the greater gravity force of the tangential component along the oblique surface. In particular, the driving effect of the inertia force and gravity is stronger than the restraining effect of the surface tension force. As a result, an upward shift in the $d_w^*$ curve occurs compared to that for the surface with an oblique angle of $\Phi = 15^\circ$. As the surface slope further increases to $\Phi = 45^\circ$, the single droplet diameter shoots up till $d_{w,\text{max}}^* = 3.35$ at $t^* = 7.5$, which is relatively higher than that for both $\Phi = 15^\circ$ and $30^\circ$ since the greater oblique angle of the surface enhances the gravity force resulting in an increase in the entire deformation curve, and then is persistent throughout.

For the two-droplet impact with $\Delta t = \Delta t_1$ as presented in Fig. 8b, the spreading diameter rises to a peak value of $d_{w,\text{max}}^* = 2.86$ over the period $t^* = 3.41-4.01$ for $\Phi = 15^\circ$ and $d_{w,\text{max}}^* = 3.77$ over the period $t^* = 4.83-6.64$ for $\Phi = 30^\circ$, respectively, owing to momentum imparted by the trailing droplet and the gravity effect. Subsequently, $d_{w}^*$ decreases monotonically and reaches a final stable value. With the inclined surface of $\Phi = 45^\circ$, the maximum extension increases rapidly up to the maximum value of 4.39 until $t^* = 7.21$ and remains approximately constant, which has the same tendency as that of the single droplet since the gravity effect becomes the dominant phenomenon.

For the case of $\Delta t = \Delta t_2$ in Fig. 8c, $d_w^*$ exhibits a brief plateau for the period of $t^* = 3.01-4.21$, and then rises to a peak value of 2.75 before decreasing rapidly in a smooth manner and finally stabilizing at $\Phi = 15^\circ$. With the increase in slanted angle, as the case of $\Phi = 30^\circ$, it is observed that the gravity effect becomes relatively important and thus leads to an increase in $d_{w,\text{max}}^*$ of 3.61 at $t^* = 9.18$. As time proceeds continuously, $d_{w}^*$ reduces monotonically toward a fixed value. As the oblique angle is raised up to $\Phi = 45^\circ$, the gravitational force becomes more pronounced and $d_{w}^*$ has an extremum and then becomes nearly constant over the remaining range of $t^*$.

For the impingement timing of $\Delta t = \Delta t_3$ and $\Phi = 15^\circ$ in Fig. 8d, the variation of $d_{w}^*$ is quite fascinating to exhibit two remarkable peaks at $t^* = 2.41$ and 8.42, respectively. After the first peak, a sudden fall till 1.89 is noticed at $t^* = 5.01$ with a subsequent augmentation to the second peak of $d_{w,\text{max}}^* = 2.68$ at $t^* = 8.42$ since the coalesced droplet stretches out toward the superradial value. Under $\Phi = 30^\circ$ and $45^\circ$, the first peak diminishes because of the increasing gravitational influence that drives the back edge of the droplet to migrate downward. After the maximum extension, $d_{w}^*$ decreases monotonically and gradually as the liquid film recoils at $\Phi = 30^\circ$, while analogous tendency of $d_{w}^*$ is discerned under $\Phi = 45^\circ$, attaining an upsurge and becoming perpetual in the remaining intervals.

![Figure 8](https://academic.oup.com/jom/article-lookup/doi/10.1093/jom/ufab012/6297654)
Figure 9 The variation of the dimensionless droplet height ($d_\text{h}^*$) with dimensionless time ($t^*$) at various conditions of oblique angles for a variety of impingement timings: (a) single droplet, (b) $\Delta t = \Delta t_1$, (c) $\Delta t = \Delta t_2$ and (d) $\Delta t = \Delta t_3$.

Figure 9 shows the variation of the dimensionless droplet height ($d_\text{h}^*$), defined as $d_\text{h}/\delta_0$, with dimensionless time ($t^*$) at various conditions of oblique angles for a variety of impingement timings. In the case of $\Phi = 15^\circ$ for all conditions of impingement timing as illustrated in Fig. 9a, $d_\text{h}^*$ has a diversity of changes in the height for case $\Delta t_3$ since the trailing droplet impinges on the leading droplet as it begins to swell resulting in a larger momentum change. At this moment, the momentum of the leading droplet prepares to accumulate in the upward direction, while that of the trailing droplet acts downward along the tilted surface after impacting, which promotes the increase in the height of the coalesced droplet. After exploring the extremum, $d_\text{h}^*$ exhibits an interval of periodic oscillation until final equilibrium states. It is worth noting that $d_\text{h}^*$ approaches the level from 0.6 to 0.7 for impingement cases of $\Delta t_1$, $\Delta t_2$ and $\Delta t_3$, but $d_\text{h}^*$ of the single droplet retains a fixed value of 0.52.

For $\Phi = 30^\circ$ in Fig. 9b, $d_\text{h}^*$ again increases significantly initially for $\Delta t_3$ and the same reasons are explained in the previous paragraph. However, the inertia effect of the trailing droplet is enhanced because of the greater oblique angle, and in turn the maximum height is also increased. Moreover, for two-droplet impingement cases ($\Delta t_1 - \Delta t_3$), $d_\text{h}^*$ converges to a final value of $\sim 0.5 - 0.6$, which is a little lower than that for $\Phi = 15^\circ$. As shown in Fig. 9c for $\Phi = 45^\circ$, due to the greater oblique angle, the inertia of the combined droplet dissipates significantly and $d_\text{h}^*$ is low compared with that of $\Phi = 30^\circ$. As a result, the final $d_\text{h}^*$ has the value of around 0.25–0.35.

Generally speaking, the result in Fig. 9 shows that $d_\text{h}^*$ has similar tendencies, which decreases initially following impact, reaches a minimum value and varies periodically prior to reaching its final equilibrium. However, $d_{\text{h,max}}^*$ becomes more noticeable for the case of $\Delta t_3$ as the oblique angle is increased from $\Phi = 15^\circ$ to 30°. Besides, as the oblique angle is further increased to $\Phi = 45^\circ$, the final $d_\text{h}^*$ converges to the lowest value compared with those of $\Phi = 15^\circ$ and 30°.

3.3 Parametric analysis of spreading diameter and vertical height

Figure 10 addresses the dimensionless maximum width and steady diameter versus surface oblique angles $\Phi$ for various impingement timings. For all different impact conditions, the nondimensional spreading diameter ($d_{w,\text{max}}^*$) increases as the oblique angle increases from $\Phi = 15^\circ$ to 45° since the effect of gravity forces becomes more remarkable at higher values of inclined angles. $d_{w,\text{max}}^*$ becomes maximal in the condition of $\Delta t = \Delta t_2$ when the collision occurs at the instant of the leading droplet reaching its maximum spreading at $\Phi = 45^\circ$, driving the droplet moving further in the direction toward the tangential component of an inclined surface. For variations of $d_{w,\text{steady}}^*$ with respect to the surface inclination, $d_{w,\text{steady}}^*$ of two-droplet impact is larger than that of single droplet due to the total volume expansion. At $\Phi = 15^\circ$, the difference in $d_{w,\text{steady}}^*$ is small at various conditions of impingement timing, but the impingement timing effect on $d_{w,\text{steady}}^*$ becomes more noticeable as the surface inclination increases. It is interesting to note that $d_{w,\text{max}}^*$ and $d_{w,\text{steady}}^*$ have the same width at $\Phi = 45^\circ$ for four different impact conditions because gravity becomes influential for behaviors of the impingement on oblique surfaces. Moreover, the effect of impact timing on the variation of $d_{w,\text{steady}}^*$ is not obvious for $\Phi = 15^\circ$, but becomes relatively pronounced with the increasing oblique angle.
The gravity effect becomes increasingly important with increasing angles of the single droplet impinging on the oblique surfaces. For all values of the oblique angle, $\Phi$, the dimensionless maximum and steady heights versus surface oblique angles $\Phi$ for various impingement timings.

Apart from droplet impact on the horizontal surface, in which the swelling occurs in the center of the droplet [33], the left portion of the merged droplet undergoes swelling asymmetrically as the oblique surface angle increases from $\Phi = 15^\circ$ to $45^\circ$, showing an irregular tendency of $d_{h,\text{max}}^*$ as presented in Fig. 11. For all values of the oblique angle, $\Phi$, $d_{h,\text{max}}^*$ of $\Delta t = \Delta t_2$ impingement condition changes apparently with the surface slope, and the maximum film height is obtained for the case of $\Delta t = \Delta t_2$. $d_{h,\text{steady}}^*$ decreases significantly as the oblique surface angle increases from $\Phi = 15^\circ$ to $45^\circ$, whereas the reverse trend is observed for $d_{h,\text{steady}}^*$. A slight $d_{h,\text{steady}}^*$ difference is obtained at $\Phi = 15^\circ$ and $30^\circ$, but the difference is enhanced for $\Phi = 45^\circ$ since the gravity effect becomes increasingly important with increasing surface slope.

3.4 Contact angles of droplets incident on solid surfaces with different surface inclinations

Figure 12 demonstrates the variation of the front ($\theta_{\text{front}}$) and back ($\theta_{\text{back}}$) contact angles of the single droplet impinging on the oblique stainless steel surfaces (note that $\theta_{\text{front}}$ and $\theta_{\text{back}}$ correspond to the left and right sides of the droplet, respectively).

In the case of $\Phi = 15^\circ$, the droplet deforms into a circular thin discoid that has both front and back contact angles of $90^\circ$ at $t = 1.0$ ms. Due to surface tension and viscous forces, the inward movement of the peripheral liquid is accompanied with reducing contact angles of $40^\circ$ and then the recoiling fluid from the edge to the center leads to increase in $\theta_{\text{front}}$ prior to final stabilization. In contrast, $\theta_{\text{back}}$ reduces to $14^\circ$ significantly attributed to the consequence of inertia and gravity of the tangential component along the oblique surface in forcing the droplet to move toward the left, and then increases after $t = 2.5$ ms because of the occurrence of contraction. For the inclined angle, $\Phi = 30^\circ$, $\theta_{\text{front}}$ maintains a constant value of $90^\circ$ as the resultant bulge shape is formed near the edge of the downstream liquid film and decreases as the swelling part of the droplet migrates toward the upstream before finally reaching a stable value, $\theta_{\text{back}}$ reduces significantly initially resulting from the droplet leftward movement, and is raised up after $t = 3.8$ ms, approaching the final equilibrium state. For $\Phi = 45^\circ$, $\theta_{\text{front}}$ has a constant value of $\sim 90^\circ$ similar to the case of $\Phi = 30^\circ$ prior to the droplet contraction. Afterward, $\theta_{\text{front}}$ degrades significantly and stabilizes at a value since the slender contour of the droplet is formed. On the other hand, $\theta_{\text{back}}$ diminishes noticeably to a minimum value of around $\theta = 10^\circ$ and increases slightly owing to the formation of a stable liquid film. It can be concluded that increasing the oblique angle decreases the stabilization value of contact angles since the final contour of the droplet becomes slender.

Figure 13 shows the variation of the contact angle ($\theta$) over time for impingement condition $\Delta t_1$ at three different oblique angles. For the inclined angle of $\Phi = 15^\circ$, $\theta_{\text{front}}$ reduces initially to around $75^\circ$ and then increases to a peak value as the liquid film moves downward along the tilted wall. Following the initial peak, $\theta_{\text{front}}$ decreases since internal flow within the droplet is retracted back from the peripheral region prior to attaining an approximately constant value. For the change in $\theta_{\text{back}}$ as the liquid film moves upward, $\theta_{\text{back}}$ increases rapidly toward an intense peak before reducing once again. Thereafter, $\theta_{\text{back}}$ increases slowly after $t = 3.8$ ms and stabilizes gradually. It is seen that $\theta_{\text{front}}$ and $\theta_{\text{back}}$ converge at a value around $\theta = 60^\circ$. For the larger inclined angle of $\Phi = 30^\circ$, $\theta_{\text{front}}$ exhibits an initial peak...
because of a swelling and then undergoes a period of oscillation before finally reaching a stable value. Conversely, $\theta_{\text{back}}$ reduces rapidly and then remains constant until the droplet starts to contact. Thereafter, it increases gradually and approaches a value close to that of $\theta_{\text{front}}$ at the angle value of $40^\circ$. For a further larger inclined angle of $\Phi = 45^\circ$, the variation of $\theta_{\text{front}}$ is similar to that of $\Phi = 30^\circ$, but retains a value of $90^\circ$ until the trailing droplet impinges on the leading one. Following the impingement event, $\theta_{\text{front}}$ rises further to a peak because of impact inertia, and then decreases to final stabilization at a value close to $\theta = 15^\circ$ due to the slender contour of the coalesced droplet. $\theta_{\text{back}}$ reduces to a minimum value from $t = 1.4$ to 3.7 ms before gradually approaching the value in the range of 10–20°.

Figure 14 shows the variation of the contact angle ($\theta$) for impingement condition $\Delta t = \Delta t_2$ at three different oblique angles. As the surface tilts at $\Phi = 15^\circ$, $\theta_{\text{front}}$ falls and rises rapidly since the merged droplet explores from spreading to accumulation. After reaching the peak, $\theta_{\text{front}}$ decreases significantly because of the recoiling fluid from the edge and stabilizes quickly. However, the oblique angle of the surface drives the droplet toward the left, and in turn $\theta_{\text{back}}$ reduces obviously at $t = 1.6$ ms. Then, $\theta_{\text{back}}$ increases until $t = 7.4$ ms and oscillates, reaching its equilibrium at a value of $\theta = 60^\circ$. As the surface further tilts at $\Phi = 30^\circ$, the trailing droplet forces the leading droplet to intensively swell after collision. Consequently, $\theta_{\text{front}}$ increases rapidly to a peak value and then falls. Once again, $\theta_{\text{front}}$ increases slightly and then stabilizes as the droplet contracts. For $\theta_{\text{back}}$, it reduces rapidly initially and then remains constant until the droplet begins contracting, at which point it gradually increases and approaches the same value as $\theta_{\text{front}}$ at the range of 40–50°. Further increasing $\Phi$ up to 45°, the variation of $\theta_{\text{front}}$ is similar to that for $\Phi = 30^\circ$ since when the oblique angle increases from $\Phi = 30^\circ$ to 45°, little change is found in the contour of the merged droplet. It is noted that $\theta_{\text{front}}$ reduces toward a value of approximately $\theta = 7^\circ$ due to its slender contour. $\theta_{\text{back}}$ reduces to a minimum value of $\theta = 16^\circ$ at $t = 1.2$ ms and changes slightly for a longer period of time before gradually approaching $\theta_{\text{front}}$, which is in the range of 10–20°.

Figure 15 presents the variation of the contact angle ($\theta$) for the three different oblique angles and the $\Delta t_3$ impingement condition. On an inclined surface, $\Phi = 15^\circ$, $\theta_{\text{front}}$ reduces to 50° and then rises to a peak and falls rapidly following the deformation of the droplet. As the droplet accumulates, migrating from the left to the right, $\theta_{\text{front}}$ stabilizes to the final equilibrium state. The variation of $\theta_{\text{back}}$ is similar to that of $\Phi = 15^\circ$ for $\Delta t = \Delta t_3$. However, $\theta_{\text{back}}$ starts to increase from its minimum value at $t = 3.9$ ms for impingement condition $\Delta t_2$, but at $t = 6.2$ ms for impingement condition $\Delta t_3$. It is noted that $\theta_{\text{front}}$ and $\theta_{\text{back}}$ reach the values of $\theta = 50–60^\circ$ finally. When the oblique angle increases to $\Phi = 30^\circ$, the trailing droplet forces the leading droplet to shift toward the left resulting in a slight accumulation of the liquid film. Consequently, $\theta_{\text{front}}$ increases from the local minimum value, and then decreases and rises one more time. Thereafter, $\theta_{\text{front}}$ increases and gradually stabilizes as the droplet contracts. $\theta_{\text{back}}$ reduces rapidly and remains constant until the droplet begins to contract. It then increases gradually toward the same value from the range of 40–50° as $\theta_{\text{front}}$. For $\Phi = 45^\circ$, the enhancement of gravity presents drastic changes in $\theta_{\text{front}}$, which explores the first peak (at $t = 2.7$ ms) and the successively decaying peak (at $t = 5.9$ ms). After that, $\theta_{\text{front}}$ reduces remarkably and stabilizes at $\theta = 10^\circ$ resulting from a slender contour. Meanwhile, $\theta_{\text{back}}$ decreases to a minimum value of $\theta = 3^\circ$ at $t = 4.3$ ms after collision and reaches to the final state of slender shapes, where the value of $\theta_{\text{back}}$ is in the range of 10–20°. For $\Phi = 30^\circ$ and 45°, the trailing droplet impinging the leading droplet causes $\theta_{\text{back}}$ to increase up and down. With the increasing oblique angle, the final contact angles with stabilization decrease and the contour of the combined droplet becomes slender.

4. CONCLUDING REMARKS

In the present work, the impact of two successive water droplets impinging onto an inclined solid surface with various oblique angles is studied. The results reveal that the evolution of two droplets impacting consecutively is highly dependent on not only the impingement timing of the leading droplet deformation but also the surface inclination. Based on the present results, the main conclusions can be obtained as follows:
1. The droplet exhibits a complex asymmetric morphology evolution, stemming from the effect of gravity caused by the surface inclination. Under various conditions of the impingement timing, the final steady shape of the droplet is far slender with increasing inclined angles due to the enhancement of gravity of the tangential component along the oblique surface, decreasing the value of front and back contact angles.

2. \( d^w \) increases initially and reaches a maximum value. After that, \( d^w \) reduces to a constant value in the stationary state for oblique angles of \( \Phi = 15^\circ \) and \( 30^\circ \), but attains an upsurge in the remaining intervals for higher oblique angle of \( \Phi = 45^\circ \).

3. The effect of the droplet impact timing on \( d^w \) becomes more pronounced at conditions of \( \Delta t_2 \), which has a diversity of changes with time. This is attributed to the large momentum interaction between the leading and trailing droplets, promoting the increase in the height of the coalesced droplet.

4. The maximum \( d^w \) occurs for impingement timing of \( \Delta t_2 \) at the oblique angle of \( \Phi = 45^\circ \), but the maximum \( d^w \) appears for \( \Delta t_1 = \Delta t_2 \) at \( \Phi = 30^\circ \). \( d^w_{\text{max}} \) and \( d^w_{\text{steady}} \) have the same width at \( \Phi = 45^\circ \) for four different impact conditions since gravity becomes more pronounced.

5. For all cases of various impact conditions, i.e. single droplet, \( \Delta t_1, \Delta t_2 \) and \( \Delta t_3 \), both \( \theta_{\text{front}} \) and \( \theta_{\text{back}} \) converge to a fixed value as time progresses, and the values become lower with the increasing oblique surface angle.

NOMENCLATURE

- \( d_h \): height of the droplet (\( \mu m \))
- \( d_h^* \): dimensionless height of the droplet
- \( d_{w,\text{max}} \): maximum dimensionless height of the droplet
- \( d_i \): initial droplet diameter (\( \mu m \))
- \( d_w \): width diameter of the droplet (\( \mu m \))
- \( d^w_{\text{max}} \): dimensionless width diameter of the droplet
- \( d^w_{\text{max}} \): maximum dimensionless width diameter of the droplet

- \( f \): frequency of the droplet generator
- \( s \): spacing between droplets
- \( t \): dimensionless time
- \( \Delta t \): interval of frames in high-speed filming (10 000 fps)
- \( \Delta t_1 \): timing of the trailing droplet impinging on the leading droplet for Case 1
- \( \Delta t_2 \): timing of the trailing droplet impinging on the leading droplet for Case 2
- \( \Delta t_3 \): timing of the trailing droplet impinging on the leading droplet for Case 3
- \( V \): impact velocity of the droplet (m/s)
- \( \text{We} \): Weber number

GREEK SYMBOLS

- \( \sigma \): surface tension (N/m)
- \( \theta_{\text{front}} \): front contact angle between droplet and solid surface (\( ^\circ \))
- \( \theta_{\text{back}} \): back contact angle between droplet and solid surface (\( ^\circ \))
- \( \Phi \): oblique angle of the solid surface (\( ^\circ \))
- \( \rho \): density (kg/m\(^3\))

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