Investigation of Binary Drop Coalescence using Dual-Field PIV Technique

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Abstract

Experiments on binary drop collisions within an index-matched liquid were conducted for Weber numbers (We) in the range of 1-50. Drop pairs of water/glycerin mixture were injected horizontally into silicone oil and, due to gravitational effects, traveled on downward trajectories before colliding. A dual-field high-speed PIV measurement system was employed to quantify drop trajectories and overall collision conditions while simultaneously examining detailed velocity fields at the collision interface. Sequences of velocity and vorticity fields were computed for both larger and smaller fields of view. In the We range examined, both rebounding and coalescing behavior occurred. Coalescence was found to result from a combination of vortical flow within drops and strong drop deformation characteristic of higher We. Flow through the centers of opposing ring vortices, strengthened by drop deformation, enhanced drainage of the thin film in the impact region, leading to film rupture and coalescence.

1. Introduction

Liquid drop coalescence in liquids occurs in many applications including manufacture, transport, mixing and separation of petroleum, chemical, food, and waste products. For example, when crude oil is extracted from the ground, it is typically mixed with water, and the water must be removed before the oil can be transported via pipeline or tanker. In this type of practical application, predictive numerical codes are desirable because they can lead to development of more efficient devices or methods, greatly reducing costs. However, coalescence is difficult to predict and model numerically because of the presence of both macroscopic and microscopic scales. While the drop motion is macroscopic, the thickness of film between colliding drops becomes microscopic. Also, colliding drops will actually coalesce only under certain physical conditions that allow the film thickness to reduce to molecular scales and van der Waals forces to become significant.

Binary drop collisions in gases were studied extensively by both Ashgriz and Poo (1990) and Qian and Law (1997) who observed a variety of collision outcomes, including rebounding and coalescence, over a range of Weber number (We) and impact parameter (B), as shown in Fig. 1. The Weber number, which quantifies the ratio of inertial to surface tension forces, will be defined as \( \text{We} = \rho_d U_{\text{rel}}^2 D/\sigma \) in this paper, where \( \rho_d \) is the drop density, \( U_{\text{rel}} \) is the relative velocity between approaching drops, \( D \) is the drop diameter, and \( \sigma \) is the interfacial tension. Thus, higher We corresponds to faster, larger drops with lower surface tension. The impact parameter \( B \) is the offset distance between approaching drop centers normalized by the drop diameter. Hence, when \( B = 0 \), the drop collision is head-on, and when \( B \) is greater than 0, the drop collision is oblique or glancing. Extensive experiments on binary drop coalescence in liquids have been conducted in flows with negligible inertia (\( \text{We} \ll 1 \)) (see e.g. Ha et al., 2003, Yoon et al., 2005). Under these conditions, drop pairs coalesce when collisions are gentle: the drops do not deform significantly, and coalescence occurs at a point of contact (similar to region I in Fig. 1). The previous studies used a capillary number \( Ca = \mu_s G R/\sigma \) as a criterion for coalescence, where \( \mu_s \) is the viscosity of the
suspension fluid, $G$ is the magnitude of the velocity gradient in the driving shear flow, and $R$ is the radius of the undeformed drop. Above a certain $Ca$, the drops deformed slightly and moved apart without coalescing similar to region II in Fig. 1 (see Yang et al., 2001). Salber (2004) examined drop collisions in liquid at Weber numbers where inertia was significant and observed a boundary between rebounding and coalescence for which the Weber number was of similar order to that observed for drop collisions in a gas (see Fig. 2). For example, collisions of water or hydrocarbon droplets in various gases at 1 atm yielded a boundary between regions II and III of $We = 10 - 40$ for $B = 0.$

![Fig. 1 Schematic of various collision regimes of hydrocarbon droplets in air at 1 atm. [plot taken from Qian and Law (1997)]](image1)

![Fig. 2 Regions of rebounding (left) and coalescence (right) for $\mu_d/\mu_i = 0.33$. Pink = rebounding, blue = coalescence, green = mixed behavior. [plot taken from Salber (2004)]](image2)

The main objective of this study was to understand the dynamic behavior of coalescing drops and the mechanism behind coalescence in flows with significant inertia. The details of rebounding and coalescing cases for the regime where $B = 0$ and $We > 1$, which is relevant to many practical applications, were examined using the PIV technique. In this regime, drops deform significantly, and the internal flow within drops becomes very important to the coalescence mechanism. A second objective is to provide test cases useful for the validation of numerical simulation methods.

We are interested in the velocity field near the thin film that separates colliding drops as well as the drop trajectories. The thin film has a microscopic length scale, and the drop trajectories span a much larger length scale. A small field of view can resolve the flow interaction at the interface, but larger scale flow behavior is unobservable. Therefore, a dual-field PIV measurement system was employed to capture both large and small scale fields of view simultaneously. In the following sections, the measurement system and results obtained therewith are described.

2. Experimental set up and methods

2.1 Experimental facility

Figure 3 shows the experimental setup. A plexiglas tank with a cross-section of 203 mm × 406 mm and a height of 305 mm held a layer of silicone oil on top of a layer of water/glycerin mixture. The height of each layer was approximately 11.4 mm. Two tubes with inner diameter of 6.1 mm were directed horizontally and positioned opposite each other. A pump was used to pressurize the drop fluid within the tubes, and needle valves were adjusted to control the velocity of each drop. A timing circuit controlled the opening time of solenoid valves downstream. By adjusting the
pump pressure and valve opening time, the volume and initial velocity of the drops could be varied.

The silicone oil was Dow Corning 200 fluid with viscosity of 50 cS. By adjusting the glycerin concentration in the water, the refractive index of the drop fluid (water/glycerin mixture) was matched with that of the silicone oil to eliminate optical distortion. Therefore velocity variations inside of the drops could be observed. TiO₂ particles of ~1µm diameter were added to both fluids to act as tracer particles. A fairly dense particle concentration was required in order to resolve velocity vectors in small interrogation areas corresponding with the smaller field of view. The drop fluid was made visible by adding a small amount of Rhodamine 6G fluorescing dye. Table 1 shows the fluid properties.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Material properties of fluids</th>
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<tbody>
<tr>
<td>Fluid</td>
<td>ρ (g/cm³)</td>
</tr>
<tr>
<td>Dow Corning 200 fluid (50 cS)</td>
<td>0.960</td>
</tr>
<tr>
<td>Water/glycerin mixture (46.2% glycerin by volume)</td>
<td>1.13</td>
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2.2 Dual-field PIV system

In the dual-field PIV system, the large field was set to capture drop shape evolution and trajectory, while the small field was focused on the thin film region through a coalescence or rebounding event. The large field was captured in stereo to enable assessment of the importance of out-of-plane motion and whether or not drops were in fact bisected by the laser sheet during a given sequence. The small field observed only in-plane motion. Observation of the small field in stereo is more challenging due to increased image distortion and a relatively thin depth-of-focus.

A high frequency Nd:YLF laser (Quantronix 527 DQE) was used as the light source. The pulse repetition rate was set to 1 kHz, and pulse energy was approximately 18 mJ. The beam was formed into a sheet directed vertically downward through the plane bisecting the tube outlets as shown in Fig. 3. The sheet thickness at the measurement location was approximately 1 mm.

Three high-speed CMOS digital cameras (Photron Fastcam Ultima APX) were mounted as shown in Fig. 4. Each camera has an array of 1024 × 1024 pixels with 10-bit depth. Two cameras with Nikon Micro-Nikkor 105mm lenses, oriented at ±20° to the plane bisecting them for stereo PIV, viewed a ‘large’ field of 40 mm × 40 mm, yielding a spatial resolution of 26 pixel/mm. A Scheimpflug arrangement was used between each camera sensor and lens to achieve good focus across the field of view. A single camera with Nikon Micro-Nikkor 105 mm lens, 1.4X teleconverter, and extension ring, oriented for planar PIV, resolved a ‘small’ field of 13 mm × 13 mm yielding a spatial resolution of 79 pixel/mm. Somewhat smaller fields are possible under the current illumination conditions (e.g. with a 2X teleconverter), but, in the current flow, it becomes...
difficult to center the field consistently on the zone of interest.

A LaVision timing unit synchronized the laser pulsing and camera framing, and stereo calibration and vector processing were performed with DaVis 7.0 software. The stereo cameras were calibrated using a two-level calibration target (Figure 5) illuminated by white light. Printed transparency films were mounted on both sides of a transparent plastic piece with thickness of 1.5 mm. Each film contained a square grid of crosses with 2.6 mm spacing, and the grids were staggered in the two planes.

The calibration, which was based on a pin-hole model, was corrected to fit the laser sheet position as explained in Wiencke (2005). A disparity map was determined based on cross-correlation of stereo images, and the difference between the laser sheet and calibration target positions was determined by triangulation. Then, a mapping function was determined based on the laser sheet plane.

Both large and small view vector fields were found using a multi-pass algorithm starting with 64x64 pixel interrogation areas and finishing with 16x16 pixel areas overlapped by 50%. Thus, the velocity was resolved to 0.63 mm x 0.63 mm areas in the large field of view and 0.20 mm x 0.20 mm areas in the small field. In the small field of view, particle diameters appeared as 1-10 pixels. Typically, the large field of view yielded 99% valid vectors, and the small field of view yielded 96%. Bad vectors in the small field resulted mainly from areas lacking tracer particles. Vorticity fields were determined from the velocity fields (filled with interpolated vectors where necessary) using a central difference scheme based on the overlapping vectors in the velocity fields. Thus, the vorticity was resolved to smaller length scales in the smaller field of view.

3. Results and discussion

3.1 Overall drop trajectories

Image processing software is used to identify drops within image sequences. In a given frame, a spherical-equivalent drop diameter is determined based on the maximum horizontal and vertical dimension of a given drop and the assumption that the drop is ellipsoidal in shape. For a specific flow sequence, a drop diameter is calculated by averaging the results from the 10 sequential images acquired immediately before drops deform due to impending collisions. A centroid position is determined based on the cross sectional area of a given drop. The relative velocity prior to collision, $U_{rel}$ was computed from the horizontal displacement of each drop centroid between images separated by 10 frames. The second image is chosen at the time that the drops reach a minimum separation before deforming, and the first image is 10 frames earlier. A trajectory or collision angle $\theta$ is defined as the inverse tangent of the vertical velocity divided by the horizontal velocity based on the same frames described above (see Fig. 6).
Figure 6 shows results from many cases over which $We$ was varied. Nozzle separation was also varied in order to achieve multiple collision angles for a given value of $We$. In general, drops travel on downward trajectories before colliding because of gravitational effects. As $We$ decreases, the vertical velocity becomes more significant. In general, the drops rebound when $We$ is below 10 and coalesce when $We$ is greater than 10. As expected, as $We$ increases, drop deformation increases during collisions. For $We > 20$, the deformation is strong enough that the drops become strongly dimpled before coalescence so that in the cut-away view, a local concavity in curvature is easily observed.

![Fig. 6](image)

**Fig. 6** Collision cases and resulting topology, $B = 0$

![Fig. 7](image)

**Fig. 7** Time evolution of drop collisions: $We=4$ (left) and $We=15$ (right). $t^* = t(D/U_{rel})$, where $D$ is drop diameter and $U_{rel}$ is relative velocity.
Two sequences from the ‘large’ field of view are shown in Fig. 7: a rebounding case with $We = 4$ ($D = 0.78$ cm, trajectory angle $\theta = 44.7^\circ$, and $U_{rel} = 11.5$ cm/s) and a coalescing case with $We = 15$ ($D = 0.84$ cm, trajectory angle $\theta = 21.7^\circ$, and $U_{rel} = 21.7$ cm/s). In these sequences, the value $t^* = 0$ is chosen somewhat arbitrarily. By comparing the two cases, significant differences in flow behavior can be seen. In the rebounding case, the two drops approach each other on downward angled trajectories before colliding. Before collision, the drop shapes are more spherical for the lower $We$ rebounding case. The drops deform only moderately before moving apart as they continue falling downward. The coalescing drops are initially elongated with tails due to higher injection velocities. Also, the initial trajectory angle is lower for this case. At the higher $We$, the larger inertia causes the colliding drops to deform more strongly generating a local concavity in the curvature. The film between the drops ruptures at $t^* = 2.33$. The resulting single drop oscillates in shape somewhat as it then falls downward.

![Fig. 8](image)

Fig. 8 In-plane velocity vectors [m/s] and vorticity contours [1/s]: $We = 4$ (left) and $We = 15$ (right). Red is counterclockwise and blue is clockwise.

The vorticity contours in Fig. 8 reveal a vortex ring within each drop as collision is approached. (Note that only a portion of computed velocity vectors are plotted so that trends are observed more easily). In the rebounding case, each ring rotates during the collision process to align with the local trajectory direction, and the circulation within each ring appears to decrease. In the coalescing case, the axis of each vortex ring appears to rotate less before the time of film rupture. After rupture, some of the vorticity is dissipated leaving a pattern indicative of a single downward-
moving ring. The vertical velocity contours in Fig. 9 show a local upflow in the zone between the drops as they approach each other. The upflow is stronger in the coalescing case as might be expected both from the stronger initial inertia and from the shallower initial trajectory angle. The rebounding case reveals two local maxima in downward velocity throughout the sequence shown. The coalescing case, however, shows one maximum in downward velocity beginning at $t^* = 0.78$, well before the film rupture. This difference must be attributed to the difference in horizontal inertia between the two cases. Note especially that, once the drops have deformed significantly and the film between them appears as a flat interface, the local maximum in downward velocity occurs at the interface in the coalescing case, but away from the interface in the rebounding case.

![Fig. 9 Vertical velocity contours [m/s]: rebounding, We = 4 (left) and coalescence, We = 15 (right)](image-url)

### 3.2 Detailed view of thin film between colliding drops and coalescence

To understand motion near the interface between drops that have collided, data from the small field of view are presented in Fig. 10. These images were taken at the time of maximum drop deformation. For comparison with Fig. 7, the left hand plot corresponds with $t^* = 1.18$ and the right hand plot corresponds with $t^* = 2.33$. Note that the maximum magnitudes of vorticity and velocity are much higher in the case that later results in coalescence. In both cases, each drop contains a tilted vortex ring that induces flow downward and inward toward the center plane. The maximum downward velocity of about 11 cm/s for rebounding can be seen in the streaming region inside of each vortex ring while the maximum downward velocity of approximately 18 cm/s occurs at the center plane between the vortices in the coalescing case. In the rebounding case, each ring is tilted
more downward than inward. By contrast, in the coalescing case, each ring is tilted more inward so that the downstream and upstream core sections are both located close to the center plane and thin film. This pair and the previously deforming interface on the outside of each drop induce a strong inflow as well as a very strong downflow that is maximized at the center plane. The downflow acts to thin the film between the drops eventually causing the film to rupture in this region. From this field and related sequences, then, it appears that strong drop deformation combined with vortex induction yields the appropriate conditions for thin film rupture and drop coalescence.

The coalescence or film rupture event is examined in some detail in Fig. 11. In the images before coalescence, the tracer particles within and bounding the thin film appear distorted (elongated in the horizontal direction) due to imperfect index matching which becomes apparent when the camera views a relatively flat section of interface at a glancing angle (see e.g. Mohamed-Kassim and Longmire, 2003). Nevertheless, viewing of individual particles in sequences indicates that the velocity vectors in this zone are accurate (and that most of these particles are associated with the drop fluid).

The magnified views of velocity and vorticity fields are centered on the location of film rupture near the downstream end of the thin film and coincident with the strong downflow region described above. When Fig. 11(b) is compared with Fig. 11(a), the velocity vectors in the vicinity of the interface have begun to vary in a wave-like form. These suggest the growth of a local instability immediately preceding or coinciding with the film rupture. In fact, the film has ruptured in the lower portion of the magnified zone in Fig. 11(b). From the raw image in Fig. 11(b), the rupture is observable by distorted tracer particles that have reverted to spherical shapes, and the disappearance of the cusp in interface curvature at the downstream edge of the thin film. It is also clear that particles near the interface experience sudden changes in velocity. Figure 12 shows the field shortly after film rupture ($t^*=2.43$). Note the sudden increase in downflow downstream of the rupture location caused by the local increase in surface tension associated with the rupture. In subsequent images, the highly curved interface above the rupture location retracts rapidly upward. The disappearance of the upper ‘cusp’ in curvature occurs within 5 ms or 0.13 dimensionless time units of the film rupture.
Fig. 11 Film rupture and coalescence ($We = 15$). The white squares show regions from which 3 mm $\times$ 3 mm velocity fields are extracted. Vectors show local velocity. Colors show vorticity [1/s]. Red is counterclockwise and blue is clockwise.

Fig. 12 After film rupture and coalescence ($We = 15$), $t^*=2.43$. The white squares show regions from which 3 mm $\times$ 3 mm velocity fields are extracted. Vectors show local velocity. Colors show vorticity [1/s]. Red is counterclockwise and blue is clockwise.

In understanding the film rupture, the out-of-plane velocity determined in the large field stereo
sequences is also useful. The ‘in-plane’ rupture behavior described, including sudden changes in vectors near the interface and in the drop curvature, is also observable in the larger field of view. Figure 13 shows out-of-plane velocity contours shortly before and after film rupture. The out-of-plane velocity is generally small before the film break (The uncertainty in out-of-plane velocity is of order ~0.02 m/s). Through the process of thin film retraction, the out-of-plane velocity components remain small suggesting that the film ruptures close to the plane of the laser sheet, i.e. the plane of symmetry in the flow. In Fig. 12(b), the ruptured film is retracting downward near the bottom of the film shown (y < 22 mm). The local downward velocities measure ~0.21 m/s while the largest out-of-plane value is 0.06 m/s, and surrounding out-of-plane values are near zero. By contrast if, due to instabilities for example, the rupture occurred at a location away from the plane of symmetry, we would expect to observe significant out-of-plane velocities associated with the film retraction in multiple frames. In flow sequences of numerous coalescence events (all with B = 0), such out-of-plane motion has not been observed.

![Fig. 13](image)

**Fig. 13** Out-of-plane velocity during the coalescence event (We = 15), zoomed view from large field. Color shows out-of-plane velocity [m/s]. Time interval between images is 5 ms, (a) t*=2.30, (b) t*=2.43.

## 4. Conclusions

A dual-field high-speed PIV measurement system was applied to investigate binary drop collisions in a liquid ambient so that drop trajectories and small-scale motion within drops could be resolved simultaneously. In this way, we can provide initial conditions for collision simulations as well as details of the behavior in the impact zone. In this paper, we compare collisions that result in rebound and coalescence, focusing on two specific events with We ~ 10. It appears that two key factors are important in driving film rupture and coalescence in this flow regime. First, the vortex rings within colliding drops must be oriented such that the upper and lower core sections are located close to the interface during film drainage, i.e. they must be angled to induce streaming flow with a strong component toward the centerplane. Second, the drops must collide with sufficient inertia such that they deform significantly increasing the velocity magnitude in the streaming flow. If the large velocities in the streaming flow reach the center plane, then they can induce a strong outflow in the thin film between the drops. The We = 15 case described herein showed that the vortex interaction combined with strong drop deformation caused a very strong downflow in the lower portion of the film so that the film ruptured in this region. From observation of multiple
coalescence events, it appears that the film ruptures close to the plane of symmetry. Velocity and vorticity sequences from additional events (not shown in this paper) indicate that the vortex core orientation affects the rupture location. For example, if the drop trajectory angle is increased, the drops rotate after impact so that the rupture location moves upward in the thin film. In the future, this effect will be studied more systematically by varying the injection angle of the drop fluid.

Other parameters that may affect coalescence include drop shape approaching collision (in the current experiments, drops do not achieve an equilibrium shape before collision), viscosity ratio of the two fluids, and the presence of tracer particles in the thin film. In previous experiments on drop/interface coalescence where film drainage was slow and driven by gravity, tracer particles in the film were found to increase coalescence rates (Mohamed-Kassim and Longmire, 2004). Future experiments will examine some of these effects.

Finally, in this study, out-of-plane motion near the interface was not captured in the smaller field. The details of this motion are of interest, however, in understanding film rupture, so we plan to obtain smaller scale stereo measurements. In these experiments, liquid prisms mounted external to the holding tank will be used to minimize image distortion and focusing difficulties in stereo viewing.

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References


