EXPERIMENTAL INVESTIGATION OF AN OIL DROPLET COLLIDING WITH AN OIL-WATER INTERFACE

Ulrich Miessner, Ralph Lindken, Rene Delfos, and Jerry Westerweel
Laboratory of Aero- and Hydrodynamics, Leeghwaterstraat 21, 2628 CA Delft, The Netherlands

Abstract

The buoyancy driven impact of an oil droplet on an oil-water interface is investigated using time-resolved Particle Image Velocimetry (PIV) along with high-speed Laser Induced Fluorescence (LIF). The obtained data serves two purposes: First, it will be used to investigate the possibility of optimizing the performance of high-speed PIV algorithms. Second, it will be used for validation of numerical simulations.

The continuous phase consists of a mix of corn syrup and water, which defines the viscosity as well as the refractive index. The droplet consists of a mixture of two kinds of mineral oils. These are mixed to match the refractive index of the disperse phase to that of the continuous phase. Both phases are seeded with tracer particles needed for PIV. Additionally, a Fluorescent dye is added to the dispersed phase to allow discrimination of the PIV signals originating from both phases. The LIF and PIV signals are captured by two aligned, synchronized high-speed cameras, each used for one of the measurement techniques. The high temporal resolution gives the opportunity to optimize the time separation between two correlated frames within the time series to achieve a high signal-to-noise ratio, while still being able to measure a large velocity dynamic range. An approach to estimate an optimal time separation is presented in this study.

Introduction

A large variety of physical and chemical processes involve two immiscible liquids, e.g. extraction, oil production and transport, emulsification and separation. Understanding of the motion of individual droplets and their interactions is crucial for economically and ecologically optimized design. While the behavior of single droplets is known to a large extent, the interaction of two dispersed droplets (e.g. deformation, break-up, collision and coalescence) is less understood. In the past, several studies have investigated the interaction of droplets and surfaces in order to understand the complex mechanisms involved. A number of studies dealt with the examination of droplets falling through a gas before impacting on a liquid surface. Because of the low viscosity of the surrounding gas the film between the impacting droplet and the surface drains quickly in this case: the droplet immediately coalesces. To study impact without instant merge of the two liquids, a higher viscosity of the surrounding fluid is required to establish a thin film between the surface and the droplet. Coalescence will eventually occur once the film is drained, but it is no longer directly coupled to the impact event.

Mohamed-Kassim and Longmire (Mohamed-Kassim 2003) published a study using this approach focusing their investigation on the hydrodynamics of the liquids involved in the impact. As a measurement technique high-speed-PIV with a frequency of 500 Hz was applied to the setup to visualize and quantify the fluid flow under investigation. However, by re-
cording the event at this frequency and correlating consecutive particle images, the full potential in terms of accuracy was not utilized.

In this work the highly instationary flow conditions during a droplet impact are chosen to provide a laminar test case with steep spatial and temporal velocity gradients. Performing measurements in such a flow at very high sample frequencies does not automatically provide better results if consecutive particle images are correlated: the measured displacement, which scales with the delay time between two images, can become so low that they will be of the same order of magnitude of the measurement error of the system. While the correlation of the particle images\(^1\) may be high (leading to a low percentage of 'spurious' vectors), the result will suffer from a lack in dynamic range and will thus be noisy. Increasing the time separation between two images decreases the signal-to-noise ratio (SNR) but simultaneously increases the velocity dynamic range (VDR). Depending on the flow conditions, each image pair requires an optimal time separation in order to increase the overall accuracy of the investigation.

The aim of the present study is to discover parameters, which can be utilized to adjust the separation time individually for each correlation. Additionally, it is our objective to use the data to validate numerical tools. For example our LIF data is used to detect and track the interfaces involved. The results are then compared to the recently developed Mass Conserving Level-Set (MCLS) method (Van der Pijl S. 2005), (Van der Pijl S. 2005).

**Experimental**

**Facility**

A glass tank with a square section of 50 mm width and 600 mm height is used for the investigation of the droplet impact (see Fig. 1). Between nozzle and interface a distance of 100 mm is maintained. The liquid layer on top of the bulk phase has a thickness of 50 mm. The liquids used are a glucose-water mix (C\(_6\)H\(_{12}\)O\(_6\) - H\(_2\)O) for the continuous phase and an oil-oil mixture (Shell Macron EDM 110 / Shell Garia GX 32) for the disperse phase. Values for the liquid properties are given in table 1. The refractive index of the mixtures is matched to minimize optical distortion with an accuracy of the actual value of 0.03%. Droplet and top layer consists of the same liquid.

A droplet with an equivalent diameter of \(d_{eq} = 11\) mm is generated by injecting the oil mixture into the bulk phase through a cylindrical nozzle of 60 mm length and 5 mm diameter. To ensure that this process is reproducible, the injection is driven by a computer-controlled syringe pump. The tracer particles are added to both phases (‘Sphericell 110-P-8’). The tracer particles have a nominal diameter of 10 µm to visualize and measure the flow conditions with PIV. Additionally, a fluorescent dye (‘Hostasol Yellow 3G’) is dissolved into the oil mixture in order to distinguish between the two liquids.

---

\(^1\) Expressed as the signal-to-noise ratio (SNR), usually obtained from the correlation peak height.
A thin planar light sheet is formed using a pulsed Nd:YLF laser (527 nm, New Wave 'Pegasus') in The experimental conditions mentioned above are comparable to those reported in (Mohamed-Kassim 2003). Important differences between both experiments are the restricted domain size and the motion of the impacting droplet (sinking droplets vs. rising droplets in the current study). The reason for the domain restriction is the correspondence to the numerical simulation, which is computed in a confined domain. Due to symmetry reasons, the opposite fluid motion in the set-up does not have significant effects when the results are compared to the results presented by (Mohamed-Kassim 2003). A list of physical properties of both investigations is given in table. 1. Where \( U_i \) is the impact velocity, \( t_g = \sqrt{D/(\Delta \rho \cdot g / \rho_{\text{mean}})} \) means the gravity timescale and \( t_i = D/U_i \) is the impact time scale. \( We = \rho_d U_i^2 D / \sigma \) and \( Re = \rho_s U_{\text{scm}} D / \mu_s \) use the index 's' for surrounding and 'd' for droplet.

|                  | Mohamed-Kassim & Longmire | present/ DNS |
|------------------|-----------------------------|--------------|
| \( D \)          | 1.03                        | 1.03         | 1.1           |
| \( U_i \)        | 13.2                        | 9.8          | 25            |
| \( t_i \)        | 78                          | 105          | 44            |
| \( t_g \)        | 78                          | 80           | 49            |
| \( \rho_d / \rho_s \) | -                           | 1.189        | 1.178         | (1.625)^{-1} |
| \( \mu_d / \mu_s \) | -                           | 0.33         | 0.14          | 0.03          |
| \( Re \)         | -                           | 68           | 20            | 36            |
| \( We \)         | -                           | 7            | 3.8           | 28            |
| \( Fr \)         | -                           | 1            | 0.6           | 0.6           |

**Tab. 1: Experimental conditions.**

**Evaluation procedures**

The processing of the obtained images from the experiments consists of two parts: extraction of droplet location and shape (from the LIF data) and measurement of the fluid velocity field (from the PIV data). The former will be compared to numerical studies (Coyajee E. 2005). The latter data is used to study the possibility of optimizing the time separation between two correlated images.
**LIF processing**

The evaluation of the LIF images is performed in Matlab 7.0. First, each image is converted to a binary bitmap using a threshold filter (see Fig. 2). The threshold value is a fixed value for the entire image series. From the resulting binary images, the following parameters are extracted:

- position of the interface
- the droplet top position
- the center of mass
- the bottom of the droplet
- horizontal and vertical diameter

Furthermore, using an edge detection method (Sobel), the shape of both the droplet and the deforming interface is captured. This information will also be used to identify the different phases in the PIV results.

![Fig. 2: Processing of the LIF images.](image)

**PIV processing**

A correlation between two consecutive raw images will produce a vector map with excellent correlation peaks due to a minimal particle image displacement. However, the separation time $dt = 333 \, \mu s$ between the two frames is too short - for these flow conditions - to result in an acceptable measurement: the displacement will be in the order of magnitude of the measurement error. However, the amount of spatial and temporal information present in the high-speed recordings allows an optimization of the separation time and thus measurement accuracy. This allows us to more accurately capture spatial and temporal gradients that occur in the flow under consideration.

To study the effect of the separation time on the resulting velocity field, the data of a single measurement set are processed multiple times, with varying separation times. This separation time is adjusted by skipping a certain number of frames in the image series (see Fig. 3).

![Fig. 3: Adjustment of the separation time: three images are skipped in this example, so that the effective separation time between frames n=-2 and n=+2 is 4 x dt](image)

The cross-correlation uses a decreasing interrogation window size starting with 32 x 32 pixels to estimate the pre-shift for two subsequent correlations using 16 x 16 pixel interrogation windows with 50% overlap. The obtained vector field is subsequently post-processed using the universal outlier detection algorithm (Westerweel J. 2005). The entire time series is evaluated in this manner with a constant value of $k$. This process is repeated for a range of values from $k = 0$ to $k = 40$. The results of this analysis will be used for the new optimized processing method (described later).
Results and Discussion

PIV: Adjusting the time separation

Based the occurrence of spurious vectors a first survey on the quality change of the vector fields is performed. The series is evaluated with a constant time separations reusing the same dataset. The time separation is increased by correlating consecutive images - number of skipped images $k = 0$ - up to a time separation using 40 skipped images to enlarge the time delay in between. A survey is performed on the data sets calculated counting the amount of spurious vectors that appear in each vector field (see Fig. 4).

Fig. 4: Survey of percentage of spurious vectors over time and separation time $k$.

This overview shows an oscillation of the percentage of spurious vectors during the impact of the investigated droplet. Increasing the number of skipped images $k$ magnifies the amplitude of the oscillation. A Comparison of the percentage of spurious vectors of the evaluated series with $k = [0, 2, 5]$ (see Fig. 5a) indicates that the evaluation failure is very sensitive to the separation time. All series show a maximum of spurious vectors near the vector field no. 212. Comparing the development of the absolute particle image displacement, standard deviation of the mean velocity of the vector field and – as an indicator for acceleration - the change of the absolute particle image displacement over time, it can be shown that the occurrence of spurious vectors is not related to the temporal gradients of the flow but to the spatial (see Fig. 5b). Furthermore the maximum of the standard deviation falls on top of the maximum percentage of spurious vectors, which indicates that this parameter can be used as criteria to adjust temporal separation of two correlated images throughout the high-speed time series.

Fig. 5a: Percentage of spurious vectors of the time series using time separation with $k = [0, 2, 5]$.

Fig. 5b: Maximum of absolute particle image displacement, RMS of the vector fields and the change of displacement (acceleration).
A closer investigation of the RMS of the mean particle image displacement over time and separation time (Fig. 6a) shows that the value of the RMS scales linearly with the separation time. Normalizing the RMS developments with the separation time shows the evolution of the standard deviation throughout the times series is self-similar. Thus, the change of the standard deviation is predictable for all variations of the separation time. Taking the influence of spurious vectors on the RMS into account it possible to adjust the separation time according to the evolution of the RMS (see Fig. 6b).

Choosing a threshold in a range where the RMS statistics are not effected by spurious vectors and still large time separation is possible allows to establish a link between an optimal separation time and the time line of the evaluated series. This smooth function has to be translated into discrete natural numbers in order to pass it on to a sorting routine that assembles a new time series with an accordingly adjusted time separation (see Fig. 7).

Due to the discrete nature of the variability of the separation time the rounding procedure used does not produce a constant value of spurious vectors. In Fig. 8 the production of spurious vectors of the resulting series is compared to the spurious vector production of series with a fixed time separation of k = 0 and 5. The optimized time series shows that the amount of spurious vectors is reduced beneath a limit of 5%. The periodic dependency on the flow conditions can not be recognized any longer and the percentage of spurious vectors is limited to an almost constant range.
Comparing the vorticity plots from Mohamed-Kassim and Longmire with the results from this study it can be shown that the results obtained with an adjustable time separation \( k \) are smoother and more detailed than the noisier results of the referred paper. The curl of the liquid inside the droplet as well as in close neighborhood to the surface impacted on is represented in more detail.

**LIF: Comparison of Simulation and Experiment**

The results produced by the LIF part of the experiment are shown in this part and can be compared to the computational results done by (Coyajee E. 2005). As a qualitative approach the droplet shape during characteristic phases of the impact can be seen in Fig. 9. The upper sequence shows the simulated sequence while the lower part compares the experimentally captured shapes. During first stadium the droplets observed during the experiments aren't in the field of view. The following stages of motion are captured well. Except the fact that the film between drop and surface is drained early differs in the simulation. Therefore viscous liquid in the bridging gap cannot influence the shaping of the droplet enough.

**Fig. 9: Qualitative comparison of the computed (top) and the measured Droplet shape (bottom).**

To compare simulation and experiment quantitatively three parameters are chosen to hint to the computations performance in predicting the motion of an oil droplet impacting on an oil-water interface:

- \( y \) position of the center of mass
- \( y \) velocity of the center of mass
- horizontal and vertical diameter (aspect ratio)

The parameters are presented in a non dimensional style in order to enable easier comparison to other experiments (see Fig. 10). The left \( y \)-axis shows the center point position of the droplet - simulation and experiment. The right \( y \)-axis shows the derived and measured velocities. Dash-dotted and continuous lines indicate different grid sizes used for the computation. Points indicate experimental data. The simulation of the droplet center point motion matches the measurement data closely. Comparing the predicted aspect ratio of the impacting drop with measured values it can be seen that the oscillation of the droplet can't be calculated in the same accuracy as the droplet motion is (see Fig. 11).

**Fig. 10: Center point position and velocity of the simulation (lines) is compared to the experimental results (points).**

**Fig. 11: Simulated aspect ratio (strong oscillation) compared to the experimental values (weak oscillation).**
Conclusion

A new approach to improve the evaluation quality of high-speed PIV has been introduced. Spatial and temporal velocity gradients cause PIV to have evaluation problems. Large time distances result in decorrelation with spurious vectors as a result. Small times distances provide a very good SNR but aren't reliable because the image displacement measured is found to be in the range of measurement error. Taking into account the flow conditions looked at an adjustable time separation between two correlated images is proposed. In order to find an optimal time separation with in a high-speed measurement, a link between spurious vectors and the time line of the captured images is needed. Based on an analysis of the flow properties with standard evaluation methods the RMS of the particle image displacement of the vector field is found to be an indicator for spatial gradients in the considered flow. Keeping the RMS constant over time and just below the threshold for the occurrence of spurious vectors provides the possibility to adjust the separation time to the flow conditions measured. Further work has to be done in order to explore the possibility to use an adjustable separation time not only related with entire images but also for each interrogation window of a vector field. In this manner it will be possible to calculate vector fields with an optimal particle image displacement throughout the whole vector field series and within each field.

The comparison of the experimental data presented in this study with numerical calculations presented by (Coyajee E. 2005) reaches at this stage a basic level. The parameters extracted from the experiment can only provide general statements about the simulation's capability to predict the flow conditions aimed at. The qualitative and quantitative parameters chosen show a reasonable capture of droplet shape and good results for the simulation of the center point motion and velocity. The difference in aspect ratio may be partially explained with the fast drainage of the thin film of viscous fluid in the simulation. However, judging the capability of the numerical simulation may be topic of future detailed investigation of the now improved PIV data set.

References

Mohamed-Kassim Z. and Longmire E., 2003, Drop impact on a liquid-liquid interface, Physics of Fluids, 15, pp 3263-3273
Van der Pijl S., 2005, Computation of bubbly flows with a Mass-Conserving Level-Set method, PhD thesis, Delft University of technology
Van der Pijl S., Segal A., Vuik C. and Wesseling P., 2005, A mass-conserving level-set method for modelling of multi-phase flows, Int. J. Numer. Meth. Fluids., 47, pp 339-361
Coyajee E., Delfos R., Slot H. and Boersma B., 2005, DNS of droplet impact on a liquid-liquid interface using a level-set/volume of fluid method with multiple marker functions, Direct and large Eddy Simulation VI, Kluwer
Adrian R. J., 1991, Particle-Imaging Techniques for Experimental Fluid Mechanics, Annual Review of Fluid Mechanics, Vol. 23, pp 261-304
Raffel M., Willert C. and Kopenhans J., 1998, Particle Image Velocimetry, Springer
Westerweel J. and Scarano F., 2005, Universal outlier detection for PIV data, Exp. Fluids, 39, pp 1096-1100