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Automated image analysis for trajectory determination of single drop collisions

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ABSTRACT

The fundamental analysis of drop coalescence probability in liquid/liquid systems is necessary to reliably predict drop size distributions in technical applications. For this crucial investigation two colliding oil drops in continuous water phase were recorded with different high speed camera set-ups under varying conditions. In order to analyze the huge amount of recorded image sequences with varying resolutions and qualities, a robust automated image analysis was developed. This analysis is able to determine the trajectories of two colliding drops as well as the important events of drop detachment from cannulas and their collision. With this information the drop velocity in each sequence is calculated and mean values of multiple drop collisions are determined for serial examinations of single drop collisions. Using the developed automated image analysis for drop trajectory and velocity calculation, approximately 1–2 recorded high speed image sequences can be evaluated per minute.

1. Introduction

The understanding and successful description of liquid/liquid dispersions is important for many technical applications. Process operations like e.g. mixing, extraction, or separation inherently comprise dispersions and also many products like e.g. milk or cosmetic creams and lotions consist of or contain emulsions which are stabilized liquid/liquid dispersions. The performance of the processes and the product quality are mainly determined by the drop size distribution of the dispersion. The droplets within the dispersion can either break due to turbulent eddies and shear stress or confluence after a collision of two droplets which is known as coalescence. The two phenomena drop breakage and coalescence determine the drop size distribution. State of the art modelling approaches describe the drop size distribution by separate kernels for breakage and coalescence rate. These so called population balance equations allow the separate implementation of breakage and coalescence which occur simultaneously in a general dispersion (Liao and Lucas, 2009, 2010; Ramkrishna, 2000). Several research groups investigated the breakage (Maaß and Kraume, 2012; Solsvik and Jakobsen, 2015a, 2015b; Nachtigall et al., 2015) and coalescence (Kamp and Kraume, 2014; Villwock et al., 2014; Eiswirth et al., 2012; Kopriwa, 2014) separately in order to validate and improve these modelling approaches. The investigations use digital high speed cameras to obtain a high spatial and temporal resolution. The use of high speed imaging is necessary because the interesting time scales lie in the order of microseconds and even below (Thoroddsen et al., 2008). The analysis of the generated data is a crucial aspect especially for serial examinations which are necessary for randomly distributed events like coalescence. The huge amount of recorded image sequences has to be analyzed automatically by applying specific computer vision methods.

This paper proposes a first step in the direction of fully automatic coalescence detection: Based on the test cell described in Kamp and Kraume (2014), a system is developed to automatically detect and track drops within the videos. From the established trajectories the time points of drop detachments as well as drop collision are reliably determined. This allows on the one hand to derive physical parameters (such as rise velocity) that are known to have a substantial influence on the coalescence probability and on the other hand restricts the amount of data in which coalescence might happen.

1.1. Coalescence in liquid/liquid systems

During a collision of two droplets with a certain relative velocity, the droplets deform each other and a thin liquid film of continuous

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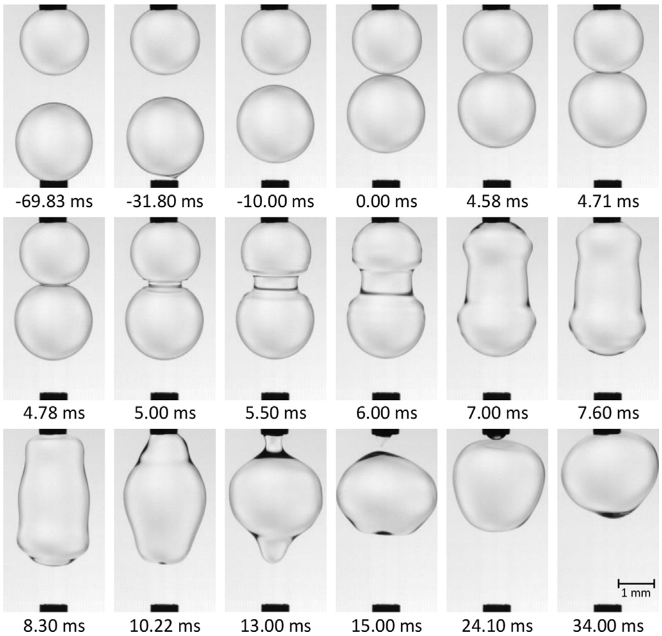

Fig. 1. Image sequence of two coalescing drops (d_{top} = 2.0 mm, d_{bottom} = 2.2 mm) recorded with VisionResearch Phantom v711 (camera system (3)) at 100,000 frames per second. The time of visual 'contact' is set to t = 0 s. Full video sequence in Supplementary material.

phase is enclosed between the opposing surfaces of the drops. This film is so thin that the drops seem to be in contact with each other in visual observations (see Fig. 1 at t = 0.00 ms). The film drains during further interaction of the droplets and the distance between the interfaces diminishes. If the "contact" of the drops lasts long enough for the film to drain sufficiently, a certain critical distance between the droplet surfaces is reached at which the interfaces merge spontaneously (also referred to as critical film thickness). The moment and point at which this film rupture occurs is affected by natural fluctuations and makes the coalescence a stochastic process (Radoev et al., 1983). After the film rupture (see Fig. 1 at t = 4.71 ms) a coalescence bridge is built (see Fig. 1 at t = 4.78–6.00 ms). The interfacial tension drives the confluence of the drops by contracting the mutual surface (see Fig. 1 at t > 7.00 ms). The steps of drop collision, deformation and film drainage are mechanistic and can be described by several models available in literature (Liao and Lucas, 2010). The stochastic phenomenon is the moment at which the draining film ruptures and coalescence occurs. Therefore, common modelling approaches describe the mechanistic parts and assume a mean critical film rupture thickness as coalescence criterion. Furthermore, the models account for the stochastic film rupture by predicting only coalescence probabilities within a droplet swarm and do not predict single coalescence events. So-called film drainage models regard the drainage and contact times as random variables and put them in relation to each other (Liao and Lucas, 2010). In the model representation of film drainage a repulsion of drops after collision can be explained as follows: if the drainage of the thin film takes longer than the contact time of the droplets they repulse each other elastically and do not coalesce. The velocity and the manner of film drainage depends on various influencing parameters i.e. physical properties of the phases (density, viscosity), interfacial tension, surface active components, dissolved ions, pH value, mass transfer, relative velocity, oscillations, drop sizes, and many more (Jeffreys and Davies, 1971). Even under apparent constant conditions coalescence itself is a stochastic event and the result of a single droplet collision (coalescence or repulsion) is not predictable. The drop shapes appearing in Fig. 1 are representative for the coalescence events recorded. The drop sizes vary from d = 1.5–3.0 mm in the experiments so that also unequally sized droplets collide with each other.

1.2. Image analysis

The current experimental set-up states several challenges that need to be handled by the data analysis modules.

1. It is not sufficient to merely detect the drop in the image, but its exact position as well as 2D radius has to be determined. The video-based estimation of the target variables (such as drop velocity and contact angle) requires a certain accuracy of the drop localization. Any measurement error at this stage has a direct influence on the final results.
2. The images of the droplets are virtually untextured due to the transparency of the fluids. Only the light dispersion on the surface of the droplets causes weak intensity gradients in the images, which frequently diminish locally during drop movement. This already weak optical signal is further degraded by the high speed cameras. The extremely short exposure times of these cameras require a strong illumination. Even high power LEDs cannot guarantee a constant and homogeneous lighting during the whole image acquisition. Due to inhomogeneities in the LED fields or vignetting by the camera lenses, the images are degraded by global gradients in intensity as well as local image noise. The weak texture of the objects on the one hand and the relatively strong artefacts of the image acquisition process on the other hand require a robust image-based tracking system, which is able to resolve such issues.
3. Last but not least, the large amount of data is a challenge by itself. Although a high accuracy of the drop localization under difficult image characteristics is required, it is not feasible to apply highly complex, time consuming methods. The data is analyzed offline without any need for real-time processing. However, hundreds of video sequences (i.e. 3–8 gigabyte of data) per parameter set have to be analyzed to obtain a sufficient sample size.

2. Materials and methods

2.1. Experimental set-up

The coalescence investigations were performed in a test cell designed for the collision of a rising drop with a pendant drop fixed on a vertical cannula. The applied liquid phases were toluene as disperse and water as continuous phase according to the EFCE standard test systems for extraction (Misek et al., 1985). The entire automated set-up was described in detail by Kamp and Kraume (2014). Using Hamilton syringe pumps the drop volumes could be determined precisely and drop sizes between 1.5 and 3.0 mm were investigated. The relative collision velocity of the droplets was determined by varying the rising distance of the bottom drop, which was detached from a cannula at the bottom of the test cell. Therefore, the distance between the cannulas could be varied from drop contact up to 100 mm (Kamp and Kraume, 2014). Three different monochrome digital high speed camera systems were used to record the drop collisions:

1. Photonfocus MV-D752-160-CL-8 (maximum resolution of 752 × 582 pixels at a frame rate of 350 fps) with frame grabber board Silicon Software microenable III, Pentax TV lens 12 mm and synchronized backlight LED flash CCS LDL-TP-100/100-R.
2. Optronis CL600X2-M (maximum resolution of 1280 × 1024 pixels at a frame rate of 500 fps) with frame grabber board Silicon