Visualisation of time-resolved mixing and penetration processes during droplet collisions using PLIF

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Abstract  The present work focuses on the experimental investigation of internal mixing and penetration during binary droplet collisions with different viscosities. A new method has been developed to analyse the mixing and penetration of droplets with different viscosity. The method allows time-resolved recordings by means of a combination of a background illumination and planar laser induced fluorescence. In order to investigate the merging of the droplets one droplet is doped with the fluorescence marker Rhodamin B. The collision process is recorded by two Photron SA 4 high speed cameras. Monodisperse droplets (diameter between 400 and 750 µm) of two polymer solutions with different mass fractions of Polyvinylpyrrolidone-K30 (1-Ethenyl-2-pyrrolidone) were created using two piezo-electric droplet generators. An analysis of one mixture (i.e. distribution of the fluorescence marker after the collision) via image processing will be carried out. Droplets with a viscosity ratio near unity will tend to create a mixture while droplets with a large viscosity ratio show a completely different behaviour. If a smaller, higher viscous droplet collides with a lower viscous, larger droplet the smaller droplet will penetrate in the other droplet. Concerning the reversed case of a small, lower viscous droplet hitting a higher viscous droplet the smaller droplet will encapsulate the larger one forming a thin liquid film.

1. Introduction

In numerous industrial areas spray drying is used to produce powders with defined properties. At the beginning, an atomisation of a solution or suspension yields fine droplets which are subsequently dried in a hot air stream. Normally, the atomisation and subsequent droplet break-up yield a broad size distribution of droplets. Owing to their size, the residence time of droplets will vary and their viscosity will be increased as a result of the drying process. Inside the spray chamber, collisions will occur close to the nozzle [4] and in recirculation zones. Here droplets of different viscosity (depending on their residence time and hence the drying state) may collide with each other. Different collision results depending on the relative velocity, the impact angle and species data can be expected (i.e. bouncing, coalescence and separation)[5]). During the drying of a droplet its solvent will evaporate, which lead to collisions of unlike viscous droplets with a diameter ratio less than unity. In the experiments the fluorescent marker Rhodamin B is used to visualise mixing as well as penetration processes. Former authors reported mixing experiments of equal viscous or slightly different viscous droplets with an other marker for water or water ethanol mixtures in [1, 2], but both studies had in common that they used a frozen image technique yielding only time averaged data. So, these studies lack the dynamics of a single collision with the result that the observation of deformations, mixing and penetration processes of the collision complex is not possible and hence some features belonging to a certain collision type are hidden. The proposed experimental method offers high time resolution and still a very good contrast where no in-motion unsharpness occurs. Thus, it is possible to study not only the dynamic behaviour of the collision complex (outer surface) but also the internal mixing and even penetration can be analysed quantitatively. This study is devoted to the investigation of such collisions experimentally in order to analyse the effects of penetration and mixing to gain more insights of the dynamics of droplet collisions.
2. Experimental Facility

For the investigation of droplet collisions with equal und unequal viscosity, uniform droplets have to be pro-duced which was realised by using two piezo-electric droplet generators. The excited jets break up into monodisperse droplets chains. The angle between the resulting droplet chains was varied in order to change the relative velocity in a range of 1 to 3 m/s. Both liquids were pressed from two separate pressure vessels through nozzles (producer: encap biosystems) with a diameter of 200 or 300 µm, resulting in droplets between 380 and 750 µm in size. The temperature was kept constant at about 22 °C by a thermostat. The impact parameter was modified by using the aliasing method (frequency shift) [3]. Three high speed cameras (two PHOTRON SA 4 and one PCO 1200 HS), whereas the two PHOTRON cameras operated synchronously, were used to observe the collision event from different viewpoints (two cameras front or collision plane view and one camera side view). The synchronous cameras were equipped with the same lens yielding a calibration factor of 11.86 µm/Pixel. Both cameras observed the collision from the same view point via a beam splitter (50/50) but with different requirements. Whereas one camera recorded a combination of green LED back light and fluorescence of the droplets, the other camera looked for the fluorescence of the single droplets and their mixture only. Therefore special glass filters (SCHOTT) were applied to meet the requirements (see Fig. 1).

First, all filters had to extinguish the scattered laser light but had to be able to pass the LED back light. Additionally, the filter of the fluorescent recording camera also had to eliminate the LED back light. So the filters were chosen as follows: 530 nm for the camera which recorded the combination of back light and fluorescence and a 590 nm filter was equipped on the other camera. The PCO camera was positioned parallel to the collision plane. It was only used to assure central collisions in that plane and was also equipped with a 530 nm filter to reduce the scattered laser light in order to protect the camera from too much light intensity. The mixing and penetration processes were visualised with the help of the fluorescent marker Rhodamin B with a concentration of 200 mg/kg Liquid. The Laser light sheet was created by a AR+ Laser (LEXEL 3500) and has been expanded to 20 mm in height and 1 mm in width at the collision point, generating a mean Laser intensity of around 150 kW/m² (see Fig. 2).
With the experimental setup it is now possible to observe the collision as well as the mixing/penetration process synchronously time- and spatial resolved due to the application of two synchronous operating cameras, which either record a combination fluorescent droplets and non-fluorescent droplets or only the fluorescence of the collision complex at arbitrary frame rates up to 30,000 frames per second and a shutter rate of 10 µs. Now new insights of the internal structures inside the collision complex are available.

3. Results and discussion

In contrast to investigations of former authors ([1, 2]) who used a frozen image technique with limitations on the dynamics of the collision, the proposed method offers high time resolution and still a very good contrast where no in-motion unsharpness occurs. Now it is possible to study not only the dynamic behaviour of the collision complex (outer surface) but also the internal mixing and even the penetration can be analysed quantitatively. The application of a second synchronous high speed camera allows for more detailed insights of the mixing or penetration of the fluid because only the fluorescent material is visible. So, the distribution of the marker can be determined better, especially for ligaments, penetration or encapsulation of liquid. Another advantage which comes with the new method is based on the fact, that numerical researchers now have better validation data due to the high time resolution. Fig. 3 proves that the developed method works quite well and delivers good results. The interval between two frames is 100 µs. Both droplets are composed of K30 with 5 % mass fraction yielding identical viscosity. The transparent droplet carries the marker and glows due to Laser Induced Fluorescence (LIF).

It can be seen that at the initial stage a deformation of the droplet occurs and the surface disrupts after 100-200 µs, then a ligament is formed which is stretched until it collapses. Inside the ligament two layers exist, whereas the fluorescent liquid can be found on the bottom of the ligament only. The mixing in this case is quite low, only at the ends of the ligament a blend of both liquids is found.

Now we want to introduce a simple approach, which is still under progress, to calculate the concentration inside the droplet after the collision. Therefore, another example of a mixing with separation will be presented and a quantitative analysis of the marker distribution will performed. At first, the local background of the droplet surroundings is subtracted and a local in-picture two point calibration of the maximum (i.e. the maximum of marker concentration) and the minimum (i.e. zero marker concentration) of the gray level distribution is applied. Fig. 4 shows the test case of the image analysis.
The droplet marked by a rectangle in the last image of the series is analysed to exemplify the algorithm. Here only the fluorescent droplet is investigated in order to determine the grey level distribution. Fig. 5a) depicts a zoomed view of the droplet after the collision. The dark region on the left side of the droplet’s curvature results from the collision due to a low concentration of the fluorescent marker. Here a transport of the liquids took place. The picture of the grey level distribution is rotated for better visualisation and shown in Fig. 5b). In this picture two glare points are visible, which are caused by the back light illumination and a reflexion of the laser light. The red rectangle marks the peak in the grey level distribution where hardly no Rhodamin B is found. The rest of the droplet is unaffected by the collision, so no mixing occurred in the rest of the droplet despite of the region mentioned. The picture on the right side of Fig. 5 is a zoom into the mixing region (marked by a red rectangle). Here a conversion from grey level to concentration was done. It can be seen that a steep gradient of the concentration inside the mixing region exists.

In opposition to the mixing of two droplets with similar viscosity, a penetration can be observed if the viscosity ratio is raised (i.e. enhancement of the solids content of one liquid). Then a penetration of the higher viscous droplet into the lower viscous one will take place. Hence, an encapsulation can be found as a possible result. In the case of a collision of a small, lower viscous droplet with a large, higher viscous droplet an encapsulation can be observed too, although the low viscous droplet is not able to penetrate into higher viscous one, but it flows around the other droplet generating a thin layer of low viscous fluid. Both cases yield same results, although the mechanisms are different. The penetration effect is even more pronouncing if the diameter ratio is less than unity. Then a thin hose from the impact point to the encapsulated droplet is visible. Fig. 6 shows both mechanisms. Each picture is divided into the two views of the synchronous cameras. The left rows give the temporal evolution of the collision complex recorded with back light and fluorescence and the right rows show the response of the fluorescence light only. On the left side the higher viscous droplet penetrates into the other one, whereas on the right side the low viscous drop flows around the viscous one. For better comparison only every 4th picture (time interval between two pictures is 400 µs) was chosen to show the temporal development of the collision complex. Moreover, a
mixing of both layers is in both cases hardly found.

**Figure 5.** Determination of the fluorescent marker in the mixing region of the right droplet

**Figure 6.** Collision of different viscous droplets; left droplet $\eta = 2.6mP$ as, right droplet $\eta = 60mP$ as; left side of a picture series: Combination of background and fluorescence; right side: fluorescence light only

4. Summary and conclusions

The present work deals with the collision of isoviscous - and non-isoviscous droplets. A new experimental method has been developed in order to visualise the mixing and penetration process of two colliding droplets. Therefore, the fluorescence marker Rhodamine B was added to one liquid and droplets were excited by an Ar+ Laser. A combination of LED back light and fluorescence light was recorded with two synchronous cameras, whereas the second camera only recorded the...
fluorescence in order to have more details on the distribution of the fluorescence marker.

A simple approach to determine the grey level distribution inside the mixing region was used to calculate the fluorescent marker concentration after the collision of two equal sized drops with the same viscosity.

An investigation of penetration processes results in two different types of encapsulation. A collision of a small, higher viscous drop with a larger or equal sized lower viscous drop will produce a penetration of the higher viscous droplet into the other one. The second encapsulation mode is achieved when a small, lower viscous droplet collides with a larger, higher viscous droplet. Here, the fluid of the lower viscous will flow around the larger drop until the whole surface is covered. The main difference between both modes is the thickness of the lower viscous layer around the higher viscous drop. In the first case (see Fig. 6 a)) the higher viscous droplet is surrounded by a thick layer of lower viscous fluid, whereas in Fig. 6 b) only a thin layer is created. For possible applications this difference might be meaningful, especially if the encapsulated product has to be protected from oxidation or other ambient effects.

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References