Binary Collisions of Droplets with Fluid and Suspension Particles

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Abstract

The present work focuses on experimental study of binary collisions of droplets of suspensions with different solid particles concentration. The aim is to study the collision phenomena and derive dominant physical mechanisms of binary droplet collision of suspensions. For the process two suspension droplet streams of equal size have been generated by means of piezoelectric droplet generators. The drop velocities of the two streams of suspension drops have been varied systematically to change the Weber number of the collision. The results help to understand the phenomena of binary droplet collision dynamics between droplets from pure fluids and suspensions.

Introduction

Many numerical and experimental studies have been carried out in the past on binary collisions of mostly equal sized droplets from pure fluids (water, fuels, alcohols …) [1-6]. The application of these results for interpretation in other relevant technical cases dealing with different process fluids especially suspensions is limited. The outcome of this is a requirement on respective experiments with model suspensions.

In this paper the results of droplet collision investigations using different liquid and suspension properties will be presented. The formation of satellite droplets for the case of the "stretching separation phenomenon" in binary collisions of equal sized droplets is the subject of particular interest.

Experimental Work

The laboratory spray rig is shown schematically in **Fig. 1**. The central device of the set-up are two piezoelectric droplet generators. One drop generator is mounted on a three-dimensional traversing unit and the other drop generator is kept fixed. Additionally to vary the collision angles (α) the direction of the droplet streams of both droplet generators can be adjusted at different angles. In our investigations in most experiments the collision angle is adjusted as α=60°. The feed to the droplet generators is carried out with separate pressure vessels. The pressure vessels are equipped with stirring elements, which keeps the liquid moving in order to prevent sedimentation of the suspension particles. The liquid flow is forced through a nozzle by means of a pressure (p=0,4; 0,6; 0,8 and 1bar), where a jet with a defined velocity is generated. In order to produce droplets of equal size (monodisperse drops), the piezoceramic vibrator of the drop generator is excited with an electrical signal [7]. For the process two droplet streams in a diameter range of 370-380μm have been produced. The nozzle tip plates used were Pt-Ir plates (200μm thick) with single hole of 200μm diameter. The mass flow rate is controlled by a valve. The droplet velocities of the streams of liquid and suspension drops have been varied systematically to change the Weber number and impact parameter of the collision.

For visualization of the collision interactions of the drops a CCD-camera is used in combination with a matrix of LED´s for a transmitted light illumination of the droplet chain. The CCD-camera and illumination technique are placed on a separate traverse unit to enable changes of the LED´s and camera positions without disturbing the drop streams. Only one function generator is used to drive the LED´s, which is synchronized with the excitation signal for the drop generators. As a result, the collision outcome may be recorded by the CCD-camera as a standing picture.

In order to determine the effect of the suspended solid particles on the collision interactions of the drops, different model suspensions based on water with various suspended China Clay ($\delta_P = 2{,}6 g/cm^3$) particle concentrations (c_p = 5, 10, 15 and 20w.%) were used. These particles ($d_{50,3}$ = 10μm) have no spherical shape (**Table 1**).

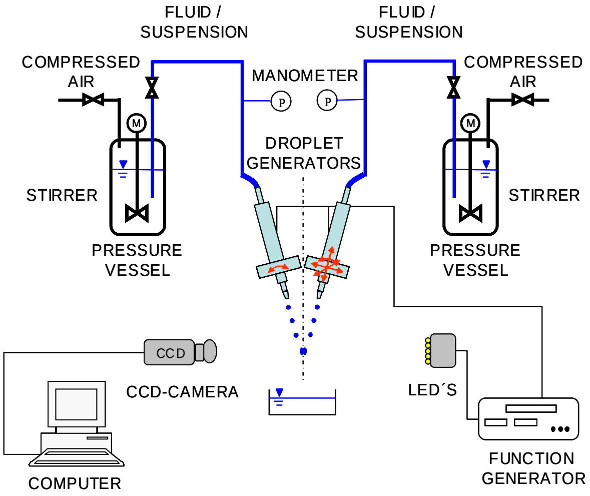

Fig. 1: Spray rig for analysis of collision interactions of the drops.

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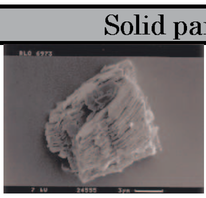
<table>
<tr><th colspan="4">Solid particle</th></tr>
<tr><td rowspan="2">China
Clay</td><td rowspan="2"></td><td>Diameter
$d_{50,3}$ [µm]</td><td>Density
ρ_P
[g/cm³]</td></tr>
<tr><td>10</td><td>2,6</td></tr>
<tr><th colspan="2">Drop 1</th><th colspan="2">Drop 2</th></tr>
<tr><th colspan="4">Water as carrier liquid</th></tr>
<tr><td colspan="2">Suspension with
c_P [w.%]</td><td colspan="2">Suspension with
c_P [w.%]</td></tr>
<tr><td colspan="2" rowspan="4">0</td><td colspan="2">0</td></tr>
<tr><td colspan="2">10</td></tr>
<tr><td colspan="2">15</td></tr>
<tr><td colspan="2">20</td></tr>
<tr><td colspan="2">5</td><td colspan="2">5</td></tr>
<tr><td colspan="2">10</td><td colspan="2">10</td></tr>
<tr><td colspan="2">15</td><td colspan="2">15</td></tr>
<tr><th colspan="4">Pure liquid</th></tr>
<tr><td colspan="2">Water</td><td colspan="2">Water</td></tr>
<tr><td colspan="4">(ρ=1g/cm³, σ=72mN/m, η=1mPas)</td></tr>
<tr><td colspan="2">30w.%Glycerine+
70w.%Water</td><td colspan="2">30w.%Glycerine+
70w.%Water</td></tr>
<tr><td colspan="4">(ρ=1,082g/cm³, σ=56mN/m, η=2,5mPas)</td></tr>
<tr><td colspan="2">50w.%Glycerine+
50w.%Water</td><td colspan="2">50w.%Glycerine+
50w.%Water</td></tr>
<tr><td colspan="4">(ρ=1,120g/cm³, σ=57mN/m, η=5,3mPas)</td></tr>
</table>

Table 1: Pure liquids and process suspensions used in the experiments at room temperature.

Results and Discussions

In the present work leadoff investigations of the collision droplets based on model suspensions were carried out, as to be more comparable with industrial processes such as spray drying, than in case of pure liquid drop collision. In order to be able to evaluate the effect of the carrier liquid by impact with solid particles on collisional interactions of the drops, the experiments have been carried out under comparable conditions as well with and as well without particle loading. For the characterization of the collision conditions the Weber number and the impact parameter were used. The Weber number (We) was defined as

$$We = \frac{\rho \cdot D \cdot u^2}{\sigma},$$

where ρ is the density, σ the surface tension, D the diameter of the liquid drop and u the relative velocity of the two drops. In the case of pure liquids the liquid density is used to define the Weber number. For the suspension drops, the density of the density mixture, dependent on the concentration of particles is utilized. The relative velocity is calculated as

$$u = (u_1^2 + u_2^2 - 2u_1 u_2 \cos \alpha)^{1/2},$$

where u_1 is the velocity of $drop_1$, u_2 the velocity of $drop_2$ and α is the collision angle (**Fig. 2**).

Second important parameter is the impact parameter (B), which characterizes the geometry of impact:

$$B = \frac{\chi}{r_1 + r_2} = \sin \psi \cdot$$

The impact parameter represents the position of the droplets χ at the moment of contact perpendicular to the direction of their relative velocity as seen in Figure 2.

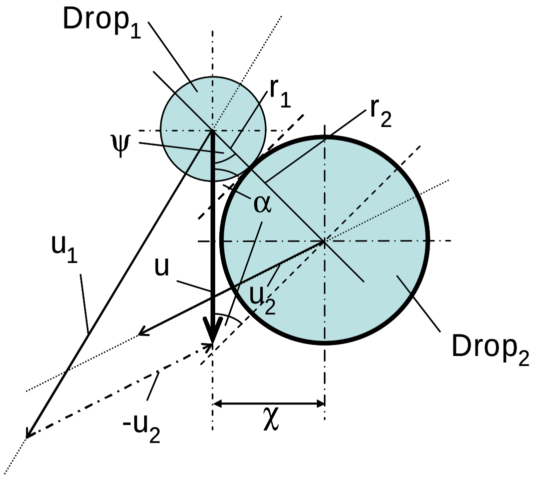
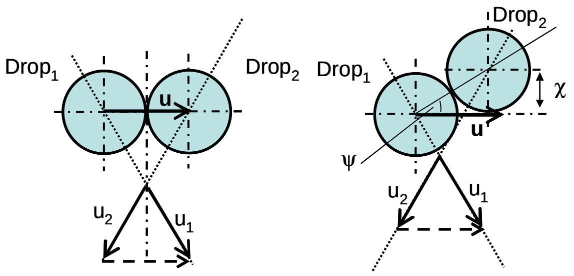


Fig. 2: Geometrical construction of the impact parameter by the collision of two moving drops of unequal size.

By considering the head-on collision of two equal size droplets the relative velocity vector coincides with the centre-to-centre line (i.e. B = 0). An increase in the impact parameter will lead to an off-centre collision (i.e. B > 0) until the droplets do not collide each other (i.e. B = 1) (**Fig. 3**).


(a)
B = 0

(b)
B > 0

Fig. 3: Geometrical construction of the impact parameter by the collision of two moving drops of equal size (a) head-on and (b) off-center.

The Weber number was mainly controlled by changing the relative velocity, which was varied by adjusting the mass flow rate. The impact parameter was varied by positioning the movable drop generator relative to the fixed one in the normal direction to the plane of view of Fig.1. The impact parameter is directly referred to the scale readings on the micrometer adjustment screw placed on the traverse unit.

The visualization system was used to record the collision outcome as a standing picture. The results were then obtained by evaluation of the records. All the experiments were carried out three times to be sure that collision conditions were reproducible.

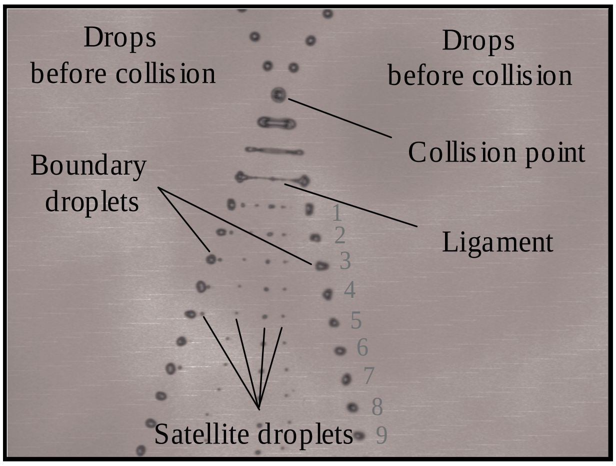
Further the formation of satellite droplets by stretching separation phenomenon in binary collisions of equal sized droplets based on liquid with and without particle loading was investigated.

Binary collision of droplets without particle loading

Figure 4a-c show results of droplet impacts using different liquids without particle loading recorded at Weber number of We = 200 and impact parameter of B = 0.83. In this figure two droplet streams of equal size are seen moving from top to bottom. The droplets collide with each other and move towards left and right. Further downwards a ligament formation process is recognizable starting from the collision point, which results into formation of satellite droplets. The satellite droplets are formed when the connecting neck is pinched off [2].

The influence of the viscosity is clearly seen in Fig. 4a-c. In the case by using water droplets (Fig. 4a) for collision process a ligament between the colliding droplets is formed. By contraction of the ligament four satellite droplets are generated in the middle of the two bigger droplets, which are called boundary droplets. Satellite droplet is a term used to identify droplets, whose diameters are much smaller than the other surrounding droplets (boundary droplets).

***(a)* Water**



***(b)* Glycerine 30w.%** ***(c)* Glycerine 50w.%**

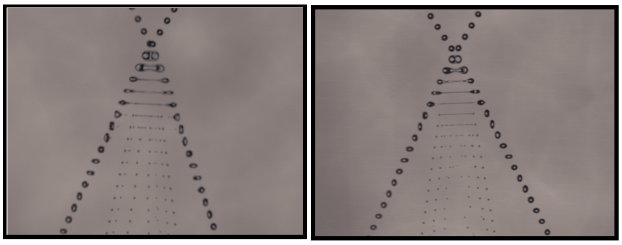


Fig. 4: Influence of viscosity (B=0.83; We=200)

By using Glycerine with 30weight% in water (Fig. 4b), the colliding phenomena is similar to the colliding case with water (Fig. 4a) but the amount of satellite droplets formed by stretching separation is higher. Comparing the results of 30w.% Glycerine with 50w.% Glycerine in water, it is shown that the higher viscosity has no significant effect on the number of satellite droplets at a Weber number of 200. The number of satellite droplets is more or less comparable to Glycerine with 30w.%. Furthermore it can be seen that the formation of two boundary droplet chains before and after collision is stable and as a result the formation of satellite droplet chains.

The analysis of the amount of satellite droplets for a defined impact parameter and different Weber numbers was done by means of an image processing tool. Comparing evaluation of occurring of satellite drops after the collisions have been made for binary collision of droplets with and without particle loading. The evaluation includes the outcome of 9 collision events i.e. 9 pairs of boundary drops and their satellites beneath the level of impact by starting counting of the first pair of drops, where the satellite drop formation is already completed. The calculated average over 9 collision events is presented in the following diagrams.

Figure 5 shows a diagram with the number of satellite droplets versus Weber number for the case of an impact parameter of B = 0.83 and different liquids without particle loading as a basis for comparisons. The satellite droplet number values for the three different liquids have a minimum at We ~ 200 and increase by increasing the Weber number. For the liquid of 30w.% Glycerine in water the measured values of satellite droplets for the Weber number in question are higher than for water. For an amount of 50w.%Glycerine in water the highest satellite droplet numbers for all Weber numbers under observation were counted.

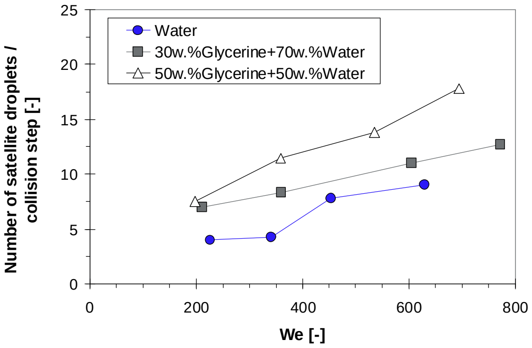


Fig. 5: Number of satellite droplets versus Weber number for different liquid drops at B=0.83.

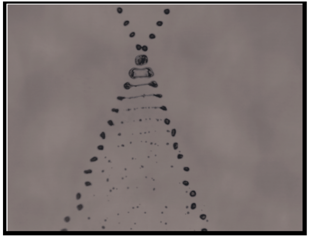
The number counts of satellite droplets for Glycerine (30w.% and 50w.% in water) can be explained by the effect of viscosity. In a liquid with lower viscosity the perturbations, leading to the ligament disintegration may grow faster. In consequence, the break-up time is decreased and the ligament length decreases. With a higher viscosity the internal friction of the fluid is so high, that perturbations are damped and the break-up of the ligament takes place in a greater distance from the two collided droplets.

Binary collision of droplets with particle loading

We consider the effect of particle loading on collisional interactions of the droplets of suspension liquids (**Fig. 6a-d**). Two droplet chains of suspensions with the same particle loading of c_p=5, 10 and 15w.% were used.

The photograph (Fig. 6a) shows an unstable formation of satellite droplets by using suspensions. This formation behaviour becomes more pronounced by increasing the particle concentration from 5w.% to 10w.% (Fig. 6b) up to a particle concentration of c_p=15w.% (Fig. 6c). Furthermore, from the presented pictures it can be seen, that by adding solid particles to the carrier liquid water, the formed satellite droplets got an unequal size.

(a) **c_p=5w.%**



(b) **c_p=10w.%** ***(c)*** **c_p=15w.%**

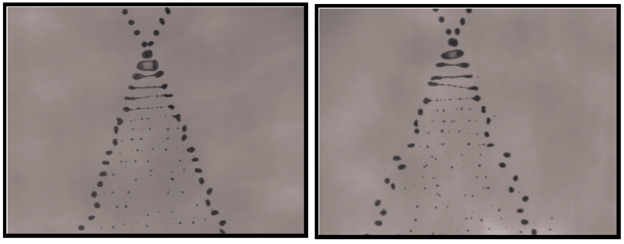


Fig. 6: Influence of solid particle concentrations (two suspension drops; B= 0.83; We~200)

The resulting number of satellite droplets for an impact parameter of B = 0.83 and different We numbers are shown in the diagram **Figure 7**.

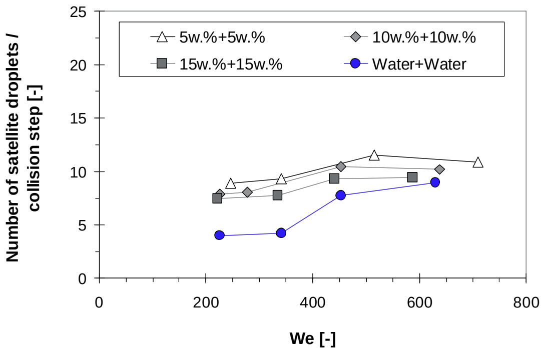


Fig. 7: Number of satellite droplets versus We number for different particle loadings of two suspension drops at B=0.83.

The number of satellite droplets for the three cases (c_p = 5, 10 and 15w.%) have a minimum for low Weber numbers and increase slightly by increasing the Weber number from We ~ 300 and strong to We ~ 450. By increasing the Weber number up to ~450 small effect on the number of satellite droplets is noticed. For the case of c_p= 5w.% the measured number of satellite droplets for We numbers in question are higher than for the case of c_p= 10w.%. By suspension drops with highest particle loading of c_p= 15w.% the lowest satellite droplet numbers were counted. For the case of water without particle loading the trends of the satellite droplet number values at different Weber numbers were the same, but the measured values were smaller. Moreover, the number of satellite droplets for Weber numbers up to ~450 increases in this case. The effect of the Weber number can be observed here.

It seems that the formation of satellite droplets is influenced by the particle loading of the carrier liquid. By increasing the particle concentration the satellite droplet number values decrease. This could be explained by the decreased length of the ligament. A higher concentration of particles in droplets of carrier liquid may stimulate the perturbations developed after the collision so high, that the local and temporal break-up of the ligament becomes faster. As a result, the number of satellite droplets decreases.

The saturation behaviour for increasing Weber numbers may also be due to the particle size, when the diameter of the ligament at break-up is in the order of the particle size.

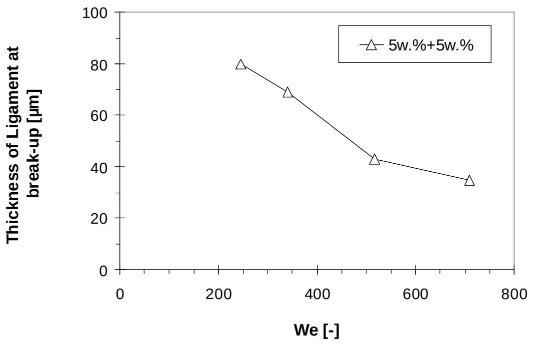


Fig. 8: Thickness of ligament at break-up versus We number for particle loading c_P= 5w.% of suspension droplets at B=0.83.

For the case of suspension droplets with identical particle loading c_P = 5w.% and for the Weber numbers under observation, the length and thickness of the ligament at break-up have been measured (**Fig. 8 and Fig. 9**). Fig. 8 shows, that the thickness of the ligament break-up decreases with increasing the Weber number while in Fig. 9 the length of the ligament at break-up is seen to increase. From these behaviour it can be noticed that at lower Weber numbers (We ~ 200) the solid particles are still good covered from the ligament. For higher Weber numbers (We up to ~ 500) the solid particles are in the order of the diameter of the ligament at break-up (30 -40µm). That means, with increasing Weber number a critical value may be reached at which the number of satellite droplets becomes constant.

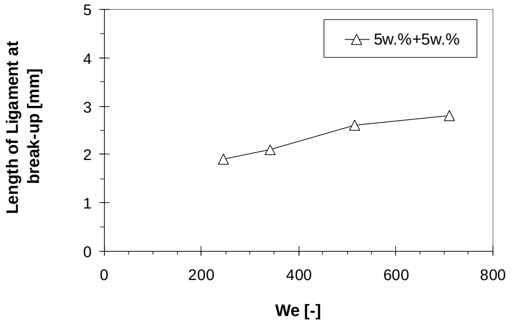
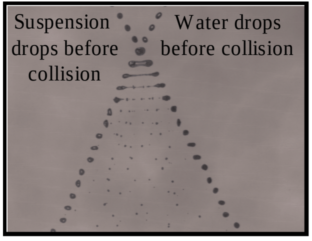


Fig. 9: Length of ligament at break-up versus We number for particle loading c_P= 5w.% of suspension droplets at B=0.83.

Binary collision of droplets from liquids with and without particle loading

In these series of experiments the collision process between suspension drops with particle concentration of c_P= 10, 15 and 20w.% and pure water drops are carried out. In **Figure 10a-c** the images of collision process between suspension drops and water drops of equal size are seen moving from top to bottom with the water drop being right. The suspension drop at different particle concentration (left) collided with the water drop and moved right while the water drop moved left.

(a) c_p=10w.%



(b) **c_p=15w.%** ***(c)*** **c_p=20w.%**

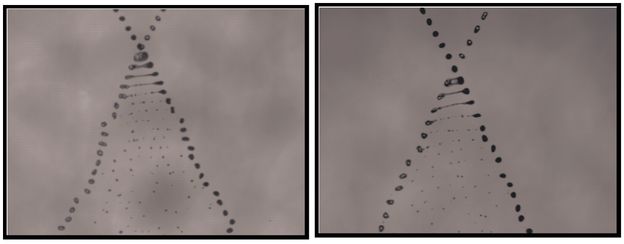


Fig. 10: Influence of solid particle concentrations (one suspension and one water drop; B=0.83; We~200)

The presented pictures (Fig. 10a-c) show similar collision phenomena as seen in Figure 6 by using two suspension drops. The particle loading of the carrier liquid here leads also to an unstable formation of satellite droplets. By increasing the particle concentration the unstable formation of satellite droplets is more pronounced.

In **Figure 11** the number of satellite droplets for an impact parameter of B = 0.83 and varied Weber numbers by using two different drops, one suspension drop with particle concentrations of 10, 15 and 20w.% and one water drop, is shown.

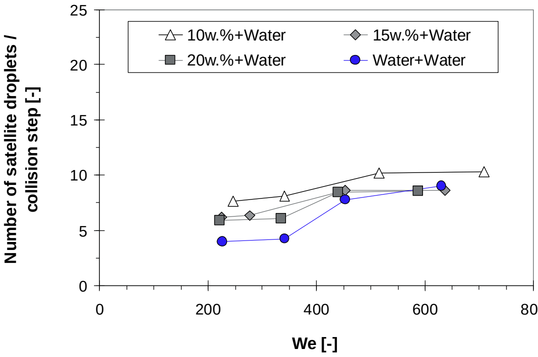


Fig. 11: Number of satellite droplets versus We number for different particle loadings of one suspension and one water drop at B=0.83.

It can be seen, that for the case of suspension drop with particle concentration of c_P= 10, 15 and 20w.% collided with water drop the number of satellite droplets have a low value at We ~ 200 and increases with increasing the Weber number at We ~ 300 but a further increase of the Weber number leads to higher values of satellite droplet number. By increasing the Weber number up to ~450 nearly the same values of satellite droplet number were measured. The effect of particle loading on the results of the satellite drop number values at different Weber number was the same as shown in the case of the collision process between two suspension drops (Fig. 7). But with the difference that these measured values were smaller.

Figure 12 shows the results of satellite drop number values for the collision process between suspension drops (c_P= 5 and 10w.%) and one suspension (c_P= 10 and 20w.%) and one water drop of equal size at an impact parameter of B = 0.83.

The satellite number values of droplets for the two cases (c_P= 5w.%; c_P= 5w.% and c_P= 10w.%; Water) have the same tendency. The number of satellite droplets have a minimum for low Weber numbers and increase by increasing the Weber number up to a maximum. For the case of different particle loading of two collided drops (c_P= 10w.%; Water) the counted values of satellite number droplets for the Weber number in question are lower than for the case with similar particle loadings (c_P= 5w.%; c_P= 5w.%). Comparing the results for the collision process of two suspension drops (c_P= 5w.%, c_P= 5w.%) with one suspension and one water drop (c_P= 10w.%; Water), which have the same particle loading at the moment of drop collision (collision point), it is shown that the different particle loading of the drops before collision has an effect on the satellite droplet number values.

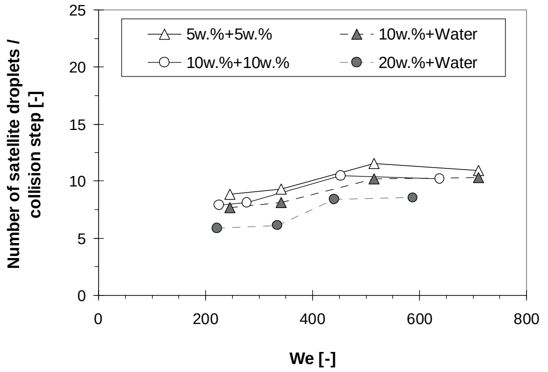


Fig. 12: Comparison of the number of satellite droplets versus We number for different particle loadings of one suspension and one water drop and two suspension drops at B=0.83.

By increasing the particle concentration of two collided droplets (c_P= 10w.%; c_P= 10w.% and c_P= 20w.%; Water) a similar trend on the results of the satellite drop number values at different Weber numbers was observed, but with the difference that these counted values were smaller.

The reason for this phenomenon cannot be derived at the present stage of the investigations. For this purpose more differentiated investigations will be done.

Conclusions

In the present investigations an experimental study of binary collisions of equal sized drops in off-center collisions has been carried out. The formation of satellite droplets by stretching separation phenomenon in binary collisions of drops of liquid with and without particle loading was investigated. In order to determine the effect of suspended solid particles concentration on the collisional interactions of the drops process suspensions based on water with various suspended China Clay particle concentrations were used. For visualization of the collisional interactions of the drops a CCD-camera is used in combination with a matrix of LED´s as illumination technique.

The evaluation of the recorded images of the collision process by using pure liquids with different properties have shown that the formation of satellite droplets for all Weber numbers under observation at an impact parameter of B = 0.83 is influenced by the viscosity effect. By increasing the viscosity the satellite droplet number values increase.

The measurements of the number of satellite droplets with a different loading of China Clay particles have shown that the increase of solid particle concentration leads to a decrease in the satellite droplet number values. It seems that the influence of the solid particle concentration is more significant than that of the viscosity.

The comparison of the satellite droplet number values for two suspension drops and one suspension and one water drop with the same particle loading at the moment of drop collision does indicate an effect of unlike drops on the collision process. The measured values of satellite droplet number by collision of one suspension and one water droplet are lower for the Weber number in question than for the case with two suspension droplets. More differentiated investigations will be done to identify this phenomenon.

Further experiments for a more detailed analysis are planned for different solid particle sizes, shapes and concentrations. In this context different impact parameters variation studies will be included in the investigations.

References

[1] Ashgriz, N.; Poo, J.Y.:”Coalescence and separation in binary collisions of liquid drops”, J. Fluid Mech., 221, p. 183-204, 1990.

[2] Qian, J,; Law, C.K.:” Regimes of coalescence and separation in droplet collision”, J. Fluid Mech., Nr. 331, p. 59-80, 1997.

[3] Havelka, P.; Gotass, C.; Jakobsen, H.; Svendsen, H.: “Droplet formation and interactions under normal and high pressure”, Proc. ICMF 2004, Yokohama/Japan, 2004, Paper No. 123.

[4] Willis, K.; Orme, M.: “Binary droplet collisions in a vacuum environment: An Experimental Investigation of the role of viscosity”, Experiment in Fluids, vol. 34, p. 28-41, 2003.

[5] Frohn, A.; Brenn, G.: “Collision and merging of two equal droplets of propanol”, Experiments in Fluids, vol. 7, P. 441-446, 1989.

[6] Blei, St.; Sommerfeld, M.:“ Experimentelle Untersuchung von Tropfenkollisionen als Basis Lagrangscher Modellierungen“, Proc. Spray 2002, Freiberg/Deutschland, 2002, p. 295-304.

[7] Ulmke, H.; Wriedt, T.; Bauckhage, K.: “Piezoelectric Droplet Generator for the Calibration of Particle-Sizing Instruments”, Chem. Eng. Technol., vol. 24, No. 3, p. 265-268, 2001.

[8] Blei, St.; Sommerfeld, M.:“Investigation of droplet collisions of viscous process fluids by imaging techniques”, ILASS 2004, Nottingham/England, 2004, p. 100-105.

[9] Brenn, G.; Kolobaric, V.:“Satellite droplet formation by unstable binary drop collisions”, Physics of Fluids, vol. 18, p. 1-18, 2006.

[10] Gao, T.-C.; Chen, R.-H.; Pu, J.-Y.; Lin, T.-H.:“Collision between an ethanol drop and a water drop“, Experiments in Fluids, vol. 38, p. 731-738, 2005.