Influence of suspended solid particles on suspension atomization processes

U. Fritsching*, B. Mulhem, O. Kurt and G. Schulte
Department of Particle and Process Technology
University of Bremen
Badgasteiner Str. 3, 28359 Bremen, Germany

Abstract

The process of atomization of liquid/solid suspensions is utilized in several industrial applications. The break-up process of suspension liquids in an atomization process differs from that of a single phase, pure liquid by the influence of the suspended particles on the fragmentation kinetics. The contribution analyses this solid particle influence on the fragmentation process of a suspension filament or sheet within the suspension atomization process.

The suspension atomization process is studied. Model suspensions with various suspended particle types are atomized. From drop size analysis it is found that the suspended solid particle size has a main influence on the resulting spray drop size distribution. The atomization of the suspension with larger solid particles may exhibit a bimodal distribution, where by the water drops separate from the solid particles. The liquid drops diameter is controlled by the solid particle size and the transfer of the aerodynamic energy to the suspension jet. On the other hand the atomization of the suspension with small solid particles shows a monomodal distribution, in which the solid particles can not separate from each other and the drops in the spray cone are suspended drops; their diameter is controlled by the transfer of the aerodynamic energy to the suspension jet. The relevant fragmentation energy determines whether the liquid disruption process is controlled by the liquid or by the solid particle properties of the suspension.

For a more detailed analysis of the suspension fragmentation process, the break-up of a stretching suspension ligament is studied. Here, the process of stretching separation and satellite droplet formation of two suspension droplets after a collision process is studied in detail. Therefore, an experimental study of binary collisions of suspension droplets in off centre collisions (impact parameter of B > 0) is discussed. 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 are varied systematically to change the Weber number of the collision. Also the type and size of suspended solid particles is changed.

Introduction

In the atomization of suspension in twin-fluid atomizers the interaction between the three different phases (solid particles, liquid and air) and the rheological properties of the suspension play are of major importance. Previous investigations have shown that the solid particle size and the solid particle concentration affect the suspension viscosity, whereby the viscosity of the suspension increases with increasing the solid particle concentration and decreases with increasing the solid particle size. Generally the suspension viscosity depends on the shear rate according to a power law ($\eta = m\,\dot{\gamma}^{n}$) in a wide range of the shear rate [1]. The suspension atomization and its rheology properties are significantly dependent on the solid particle size.

Son and Kihm [2] studied the effect of the coal particle size on coal-water slurry (CWS) atomization. They examined three different samples (32 – 45 µm, 45 – 63 µm, and 63 – 90 µm) and found that the Sauter mean drop sizes of the atomized suspensions (SMD) of the CWS containing smaller coal particles are larger than the SMDs of CWS containing larger coal particles. This may be attributed to the increasing slurry viscosity and the increase of the capillary force between the particles with decreasing particle size. Other results were presented by Cronin et al. [3]. They also found that the spray SMD data showed that CWS containing smaller particles produce larger spray droplets than CWS containing larger particles.

Dombrowski and Fraser [4] studied the break up of water and alcohol sheets containing 3 to 60µm suspended solid particles. They found that where the particles were wetted by the liquid they had no effect on the manner of disintegration of the sheet. On the other hand, when suspensions of unwettable particles are used they have a distinct effect and cause perforation of the sheet. Glaser [5] investigated the break up of suspension sheets containing different solid particles. Solid particles with a small relative density to the carrier fluid affect the sheet stability if the sheet

*Corresponding author: fritsching@iwt.uni-bremen.de

thickness is thinner than the solid particle size, while the acceleration of the solid particle with a large relative density achieves the instability and the turbulence of the suspension sheet.

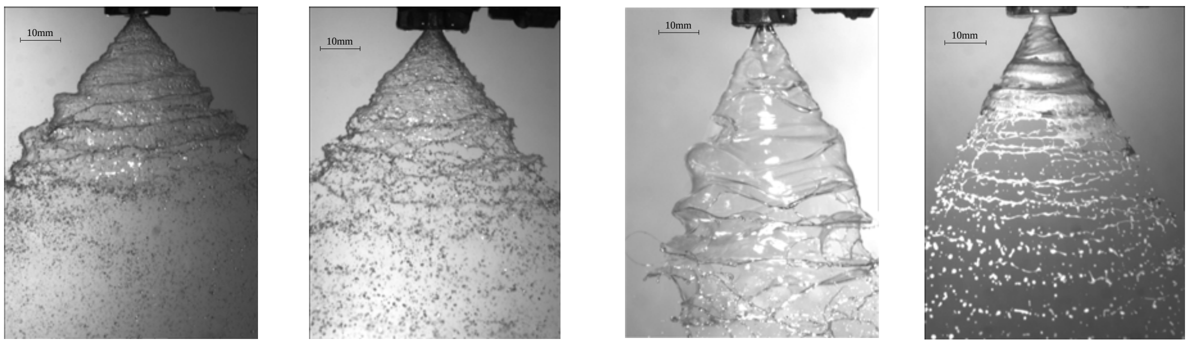
The influence of solid particles in a suspension to be atomized is subject of the present study. Suspensions are atomized in various types of atomizers to study the specific role of the solid particles on the fragmentation process. A detailed analysis of a suspension ligament break-up process is performed within the stretching separation process of two suspension drops after collision.

Materials and Methods

In this contribution the fragmentation process of ligaments and films within the suspension atomization process is studied. Main analysis method is the evaluation of photographic views of the fragmentation process itself. A pressure swirl atomizer is used for achieving a film fragmentation mode behaviour that includes the formation of holes and ligaments, respectively, while twin-fluid atomization is used as a fibre-mode desintegration process. In addition, the fragmentation of a ligament formed in between two colliding droplets in a stretching separation process after the collision is studied. Different solid particles are used for the experiments, mainly china clay and glass particles in the size range from 1 to 100 µm.

Results and Discussion

Figure 1 shows photographs of the break-up process of a hollow cone sheet of three different carrier liquids (water, Ethanol/water and Glycerol/water) and a high concentrated Clay/water-suspension (Cp = 30v.%) at the injection pressure p_{rel} = 1.2bar. The film is created by a pressure swirl atomization device. The photographs show that the hollow cone liquid sheets will disintegrate into ligaments and drops according to the aerodynamic waves. The change for the suspension fragmentation process is visible. The break-up length defined as the distance of the hole formation to the atomizer exit is decreased [6].



Water | Ethanol/water-mixture | Glycerol/water-mixture | Clay/water-suspension c_p = 30vol.%

Figure 1. Photographs of a hollow cone sheet from a swirl pressure atomizer of different carrier liquids and a suspension based on water at an injection pressure p_{rel} = 1.2bar

The influence of the solid particle size on the break-up process of the hollow cone suspension sheet is studied for two different suspension based on glycerol/water-mixture and with different glass particle fractions (35µm and 95µm). For low particle loading (c_p = 5vol.%) no significant influence of the solid particle on the suspension flow rate, on the spray cone angle and on the break-up mechanism has been observed. The only influence of the solid particle size is on the break-up length (perforation distance) Z_{hole}. The distance Z_{hole} decreases with increasing the glass particle size in the suspension (Figure 2).

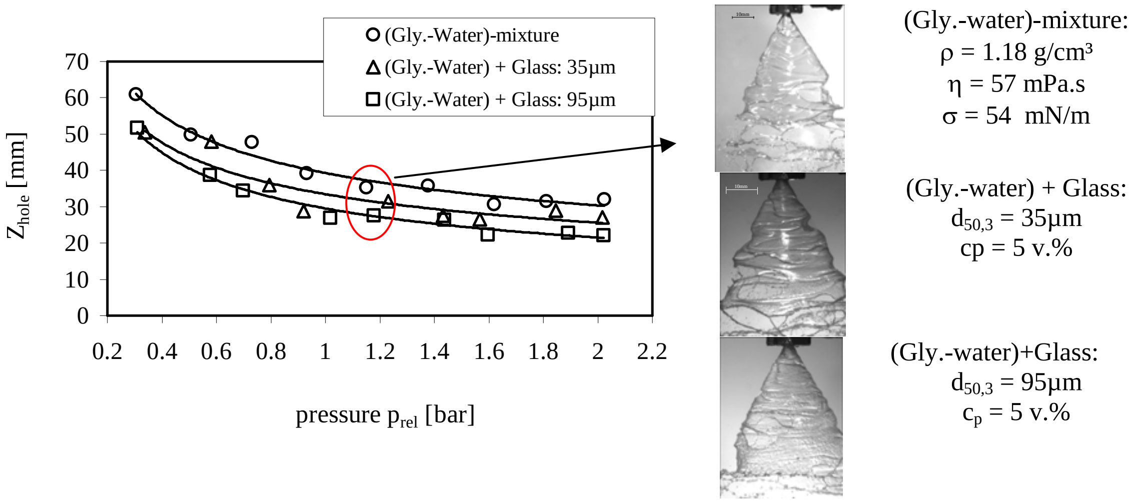


Figure 2. Sheet length at the position of the perforation for a dilute suspension (Cp = 5v.%) based on Glycerol/water-mixture and with glass particles of different size as a function of the pressure

In order to compare the sheet thickness at the position Z_{hole} with the solid particle size the sheet thickness is calculated using a method presented by Dahl [7]. The comparison of the solid particle size with the sheet thickness confirms the results presented by Glaser [5] that the suspension sheet containing high density solid particles shows perforations, where the sheet thickness is much thicker than the solid particle size. Figure 3 shows the calculated sheet thickness at the position Z_{hole} for the two glass suspensions and for the carrier liquid (glycerol/water).

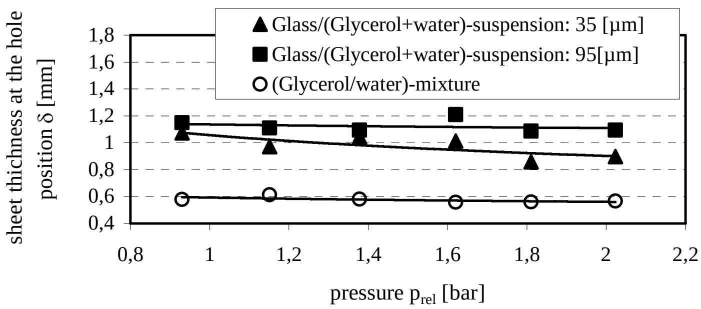


Figure 3. Sheet thickness at the hole formation position as a function of the injection pressure

The measured drop size distribution in twin-fluid atomized suspension is shown in Figure 4. Here two different types of size distribution are seen. At lower loading, the size distribution is monomodal, while for higher loading a bimodal distribution establishes. Here an effect of solid / liquid separation in the atomization process occurs that is described in detail in [8, 9].

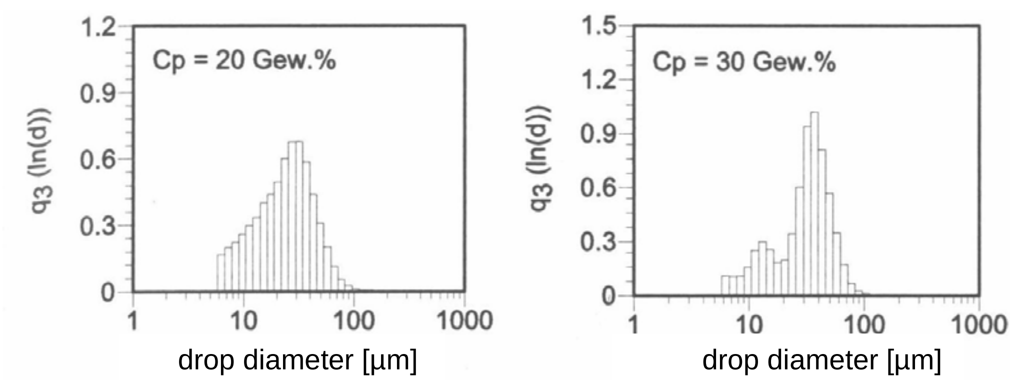


Figure 4. Drop size distribution in twin-fluid atomized suspension with solid particle size dp = 30µm

The median and Sauter-mean drop sizes in the twin-fluid atomized suspension are shown in Figure 5 versus the energy input into the atomization process, described by the product of the aerodynamic Weber number time the air to liquid mass flow ratio ALR. An identical behaviour is to be seen at lower energy input, while at a distinct point the drop size decreases for the lower concentration. Here a critical ratio of number of solid particles (acting as fragmentation promoters) an energy input into the fragmentation process is achieved. When comparing the median drop size in the atomized suspension for different particle sizes from 6 to 30 µm to the resulting drop size in a water spray, the spray drops are getting smaller in the presence of solid particles. This effect is more pronounced with increasing specific energy input into the atomization process.

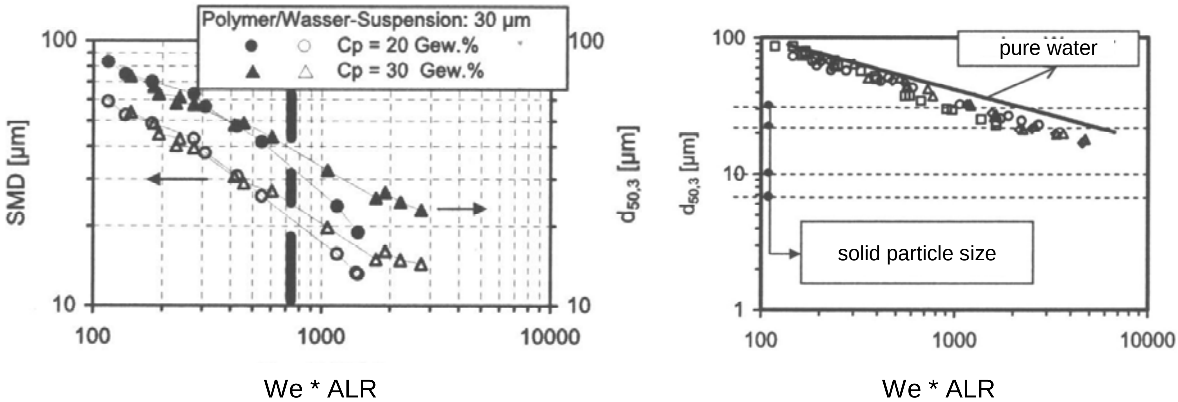


Figure 5. Droplet sizes in twin-fluid atomized suspension; left: variation of solid concentration for dp = 30µm; right: variation of solid particle size dp = 6, 10, 22, 30µm

The break-up process of a suspension filament is studied in detail by analysis of the stretching separation of two colliding suspension droplets. The droplets are created by piezo droplet generators. Two droplets of identical size are colliding at defined conditions, that are the impact Weber number and the impact parameter [10].

Figure 6 illustrates droplet impacts of equal sized suspension droplets for the case of the "stretching separation phenomenon". A ligament formation process is to be seen starting at the collision point, which finally results in the formation of satellite droplets when the connecting neck is pinched off. The satellite droplets diameter is much smaller than the initial droplets diameter. The analysis of the amount of satellite droplets was performed by means of an image processing tool.

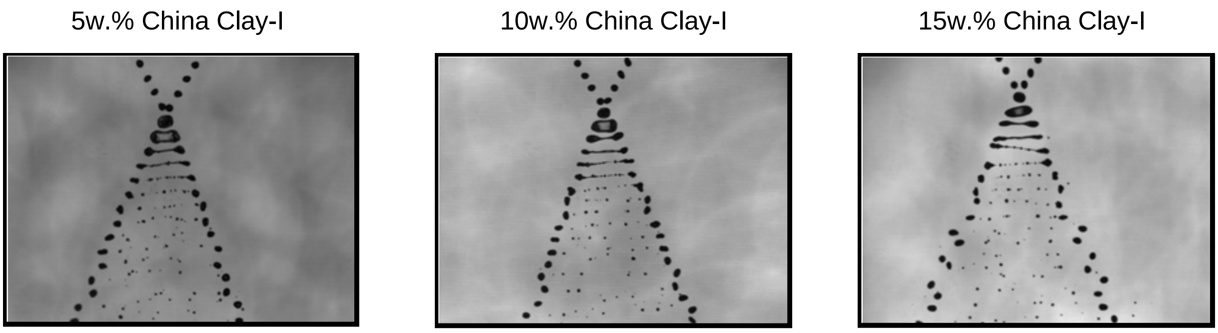


Figure 6. Stretching separation of suspension droplets after collision

When adding solid particles to the water the colliding phenomena show an unstable formation of satellite droplets to the colliding case with pure water. This formation behaviour becomes more pronounced by increasing the particle concentration from 5w.% up to a particle concentration c_p = 15w.%.

The resulting number of satellite droplets for impact parameter B = 0.83 and different Weber numbers are shown in Figure 7. The number of satellite droplets for the six cases (c_p = 0.3, 0.5, 1, 5, 10 and 15w.%) have a minimum for low Weber numbers and increases by increasing the Weber number from We ~ 300 to We ~ 450. For c_p = 0.5w.%

the measured number of satellite droplets is larger than for c_p = 1w.%, 5w.% and 10w.%, and at the highest particle loading c_p = 15w.%, the lowest satellite droplet number is counted. By decreasing the particle concentration (c_P = 0.3w.%) the satellite droplets number for suspensions decrease again to a value of the pure water. This trend is illustrated in Figure 8 for the number of satellite droplets depending on particle concentration at We = 500 and an impact parameter B = 0.83.

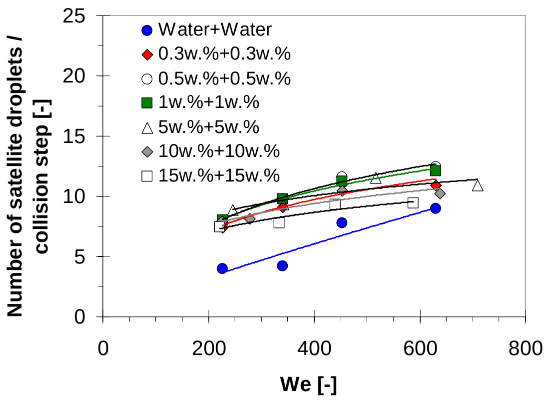


Figure 7. Number of satellite droplets versus We number for different particle (China Clay-I) loadings of two suspension drops at B = 0.83

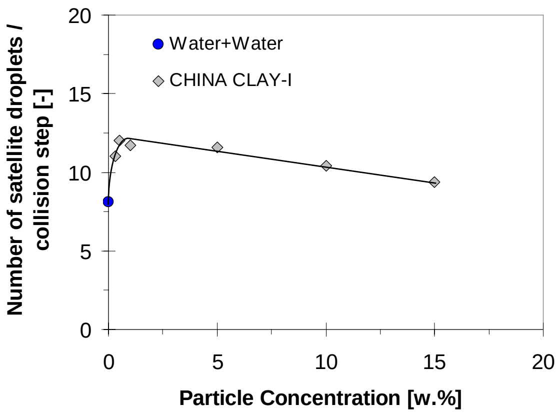


Figure 8. Number of satellite droplets versus particle concentration for China Clay-I at We = 500 and an impact parameter B = 0.83 for identical particle size $d_{50,3}$ = 10µm

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 decreases due to the decreased length of the ligament at break-up. A higher concentration of particles stimulates the perturbations developed after the collision, and spatial and temporal break-up of the ligament becomes faster. As a result, the number of satellite droplets decreases. The limiting behaviour for increasing Weber numbers may be referred to the particle size, when the diameter of the ligament at break-up is in the order of the particle size.

Figure 9 illustrates the resulting number of satellite droplets for the collision of suspension droplets with identical particle loading c_P = 10w.% when using different particles for an impact parameter of B = 0.83. The influence of the particle size on the satellite droplet formation is seen in Fig. 7. The satellite drop numbers for the investigated cases (China Clay-I – $d_{50,3}$ = 10µm, Polyamid – $d_{50,3}$ = 7µm, Silibeads – $d_{50,3}$ = 4µm, China Clay-II – $d_{50,3}$ = 2µm and water) have similar tendencies. The numbers of satellite droplets have a minimum for small Weber numbers and increase by increasing the Weber number to a maximum.

The number of satellite droplets versus the solid particle size within the suspension at an impact parameter B = 0.83 and at a Weber number We = 500 is shown in Figure 10. The number of satellite droplets decreases with increasing particle sizes. The decrease of the satellite droplet number with increasing particle size is due to the relative particle size with respect to the length, respectively the ligament diameter at break-up. However, when using pure water without particle loading, one achieves another limit which may hold for an infinitely small particle size. In this case the smallest number of satellite droplets should be observed. By decreasing the particle size ($d_{50,3}$ < 4µm) the satellite droplets number for suspensions decreases again to a value of the pure liquid. Here the suspension viscosity effect, considering the suspension with smaller particles as a colloidal system, may contribute. Further investigations with smaller particles (below 2µm) are needed in this area.

The effect of solid particles on the ligament disruption in the stretching process is illustrated in Figure 11. The particle size with respect to the actual fibre diameter is controlling the break-up process. The larger solid particles act as instability sources for the ligament break-up. Therefore the number of satellite drops in the stretching separation process is controlled by the solid particles size.

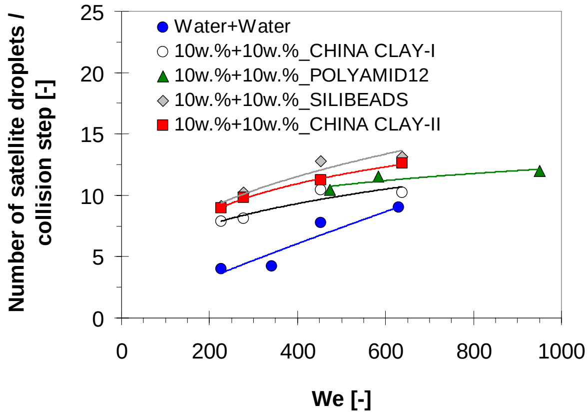


Figure 9. Number of satellite droplets versus We number for different particle types and sizes of two suspension drops at B = 0.83

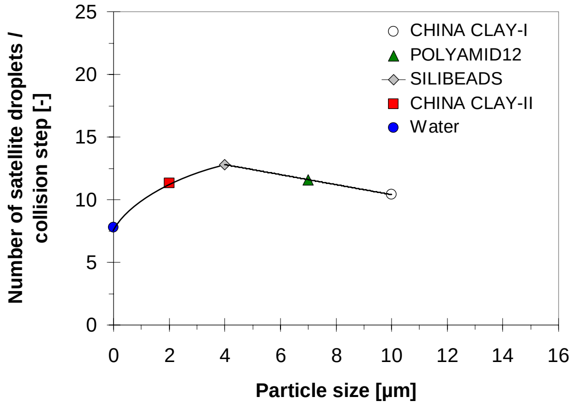


Figure 10. Satellite droplets number versus particle size for different particle types with identical particle loading c_P = 10w.% We = 500 and B = 0.83.

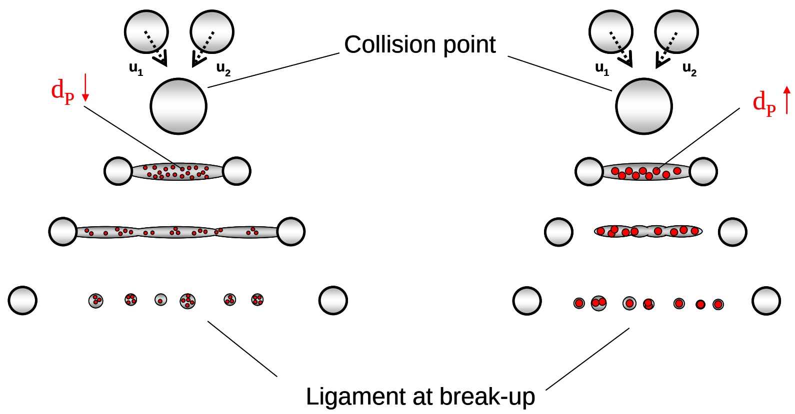


Figure 11. Formation of secondary droplets during filament stretching depending on solid particle size

References

1. Pahl, M., Gleißle, W. and Laun, H., *Praktische Rheologie der Kunststoffe und Elastomere*, VDI-Verlag GmbH, Düsseldorf, p. 391-411.
2. Son, S.Y. and Kihm, K.D., "Effect of coal particle size on coal-water slurry (CWL) atomization", Atomization and Sprays, 8, 1998, pp. 503-519.
3. Cronin, L., Sojka, P.E. and Lefebvre, A.H., "The Effect of Fuel Film Thickness on Coal Water Slurry Atomization", SAE paper 852086, 1985
4. Dombrowski, N and Fraser R.P., "A photographic Investigation into the Disintegration of liquid sheet", 1954 Phil. Trans. R. Soc. London A 247 1001-130, 1954.
5. Glaser, H.W., *Das Zerstäuben von Suspensionen mit Ein- und Zweistoffdüsen*, VDI VERLAG, Düsseldorf, 1989.
6. Mulhem, B., Khoja, G., Fritsching, U. and Bauckhage, K., „Photographic Observation of Break-up of Hollow Cone Suspension Sheet", 19th ILASS Europe 2004, 6-8 September 2004, Nottingham, UK, pp. 451-456.
7. Dahl, H.D., *Theoretische and experimentelle Untersuchungen zur Flüssigkeitszerstäubung mit Hohlkegeldüse*, Ph.D. thesis, Univ. Stuttgart, 1992.
8. Mulhem, B., Fritsching, U., Schulte, G. and Bauckhage, K., „Effect of Solid Particle Characteristics on Suspension Atomization", Atomization and Sprays 13 (2003) 2&3, pp. 321-343.
9. Mulhem, B.; Schulte, G. and Fritsching, U., "Solid-liquid separation in suspension atomization", Chem. Eng. Sci. 61 (2006) 8, pp. 2582-2589.
10. Kurt, O.; Fritsching, U. and Schulte, G., "Binary Collisions of Droplets with Fluid and Suspension Droplets", Proc. ILASS Europe Meeting 2007, 10.-12.9.07, Mugla, Turkey.