Characterisation of Twin-Fluid Atomisation for Suspensions

B. Mulhem, U. Fritsching, G. Schulte and K. Bauckhage

University of Bremen, Chemical Engineering Department
Badgasteiner Str. 3, 28359 Bremen, Germany
Phone: +49-218-2311, fax: +49-218-8221, e-mail: mulhem@iwt.uni-bremen.de

In order to characterise the atomisation process of a suspension containing small solid particles in a twin-fluid nozzle a comparison has been made between the break-up mechanisms and the resulted droplet size for several suspensions and their suspension liquids. The investigations indicate that the suspension jet disintegrates in a co-axial air stream as a pure liquid jet according to three break-up mechanisms (Rayleigh, membrane, fibre type break up). Based on the available data from liquid and model suspension atomisation an empirical formula for the droplet diameter of atomised pure liquids and suspensions has been improved by presentation of the droplet size (d_{32}, $d_{50,3}$) with the product of the $Z_{BP} = We_{aero} \times ALR$ as $d_{32} = 0.21 d_L \left(Oh\right)^{0.0622} \left(Z_{BP}\right)^{-0.4}$. Where d_L: the diameter of the liquid nozzle, Oh: Ohnesorge number, We_{aero}: Aerodynamic Weber number and ALR: Air Liquid mass Ratio.

1. Introduction

The atomisation of suspensions is a very important stage in chemical, food, and pharmaceutical industrial applications, e.g. for paints, paper coatings, printing inks, ceramics, cosmetics, detergents, and coal water slurries. In contrast to atomisation of pure liquid there is lack of studies, which investigate the disintegration of suspension in a twin-fluid nozzle.
Farago and Chigier [1] studied the disintegration of a water jet in a coaxial air stream. According to the aerodynamic Weber number We_{aero} and the liquid Reynolds number Re_L

$$We_{aero} = \frac{d_L \, \rho_{air} \left(u_{air} - u_L\right)^2}{\sigma}, \; Re_L = \frac{d_L \, \rho_L u_L}{\eta_L}.$$

They classified the break-up modes in a (We_{aero}-Re_L) diagram into three regimes (i) Rayleigh break-up $We_{aero} \le 25$, (ii) membrane-type break-up $25 \le We_{aero} \le 70$ and (iii) fiber-type break-up $We_{aero} = 70$ [1]. Following to Meyer [2] the most important processes leading to twin-fluid atomisation (water/air) are turbulence in the liquid, surface instability, surface wave growth and droplet detachment. Furthermore the surface phenomena at high liquid flow rates and medium gas velocities have been found comparable of break-up modes of single droplets as e.g. the bag- and shear break up. Further investigations from Lasheras and Hopfinger on water jet instability and atomisation in a coaxial air stream have confirmed the Farago results [3]. Detailes Studies on the break-up of suspension jets in a coaxial air stream were not published so far.

Numerous researchers have investigated the influence of solid particle size and concentration on suspension atomisation. The source of the influence has been attributed to be on the one hand the suspension viscosity, which increases with decreasing the solid particle size or increasing the concentration and on the second hand the increase of the capillary forces with decreasing the solid particle size [4] [5].

Glaser [6] compared the atomisation of water and coal-water slurry with d_P = 20 µm and Cp = 70.9 w.% by means of a prefilming-swirl nozzle. He found that only the large solid particles separated from the water droplet.

Isenschmid [7] compared the twin-fluid atomisation of various suspensions with d_p= 4 – 16 µm and Cp = 0 – 30 w.% and their suspension liquids. The results did not show a clear influence of solid particles on the droplet size resulted.

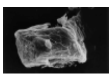
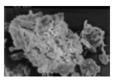
In a previuoe study Mulhem et al. [8] established that a separation process takes place by the atomisation of suspension containing large solid particles i.e. solid particles and pure liquid droplets will be found in the spray, while the atomisation of suspension with fine solid particles is comparable to the atomisation of the pure suspension liquid.

The purpose of this study is to investigate the break-up mechanisms that dominate the disintegration of suspension jets in coaxial air stream and to compare it with break-up mechanisms from literature. Further more, an approximate correlation equation will be deduced for the resulting droplet diameter in the spray based on the available data from the model experiments.

2. *Experimental Set-up*

In order to characterize the twin-fluid nozzle for suspension atomisation, the disintegration modes and the resulting spray drop diameters for various model suspensions and their suspension liquids were investigated and compared. **Table 1** shows the properties of liquids and suspensions investigated.
Fig. 1 shows a schematic illustration of the experimental set-up and the model twin-fluid nozzle. Photographs of the liquid break-up are taken with CCD-camera immediately downstream of the nozzle. The droplet size has been measured by means of the Laser diffraction method (Malvern 2600c). The experimental set up is described in detail in [8].

Table 1: Properties of suspensions used

Model suspensions							
Suspension liquid		Solid particle					
Water	ρ = 1000 kg/m³ σ = 0.072 N/m η = 0.0011 Pa.s	Glass	ρ_P = 2500 kg/m³ Cp = 50 w.% d_P = 6,22 µm	Kaolin	ρ_P = 2600 kg/m³ Cp = 50 w.% d_P = 5,10 µm	Polymer	ρ_P = 1000 kg/m³ Cp = 20 - 30 w.% d_P = 10, 28µm
Glycerine/water	ρ = 1160 kg/m³ σ = 0.056 N/m η = 0.016 Pa.s						
CMC/Water	ρ = 1000 kg/m³ σ = 0.072 N/m η_o = 0.08 Pa.s						

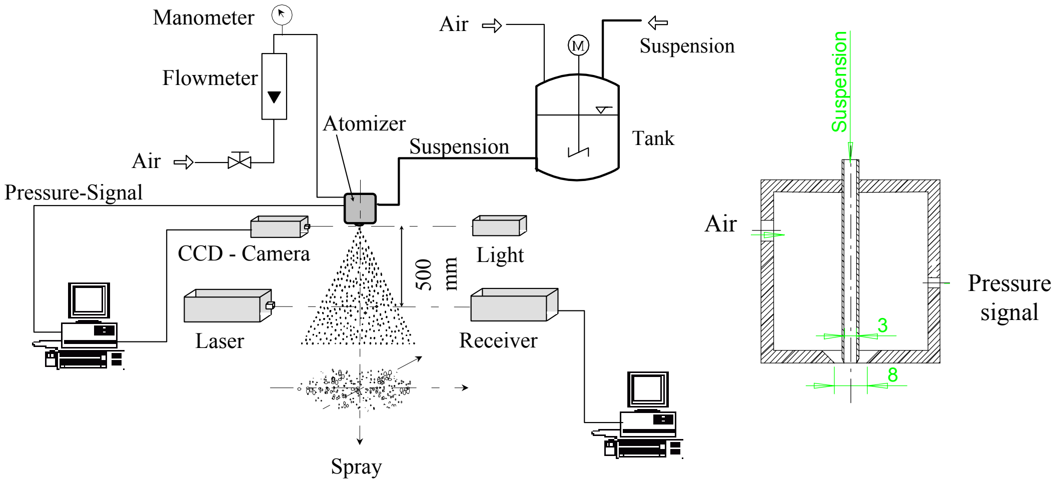


Fig. 1: Experimental set up and model twin-fluid nozzle used

3. *Results and Discussions*

3.1 *Influence of Solid Particle on the break up of the Liquid jet in co-axial air stream*

From the analysis of the break-up photographs it was found that the suspension jet disintegrates in a co-axial air stream as a pure liquid jet according to three break up mechanisms (Rayleigh, membrane, and fibre type break-up). In **fig. 2** photographs of the break-up of water and two kaolin/water-suspensions are presented for different air velocities u_{air} = 0 - 75m/s and a constant liquid velocity u_L= 1.8m/s. The solid particle concentration in the suspension is changed from 30 to 50w.%. From the comparison between the break-up of water jet and suspension jet at identical operating conditions (u_{air} and u_L) the following points are pointed out:

1. In Rayleigh regime fig. 2-I, II: The increase of the solid particle concentration leads to decrease of the surface wave growth and on the other hand to increase of the core length (break-up length).
2. In Membrane regime fig. 2-III, IV: In contrast to the water jet and suspension jet with Cp = 30w.% the suspension jet with Cp= 50w.% does not form membranes. The break-up of suspension jet begins with the formation of ligaments and their peeling off the main suspension core, which breaks up according to Rayleigh regime.
3. In fiber regime fig. 2-V, VI: The points of interest are the increase of the core length and the increase of the formed ligaments size with increasing the solids concentration in the suspension jet.

It is assumed that the explanation of this behaviour is the increasing of the suspension viscosity with increasing the solids concentration. Measurements have shown, as expected, that the suspension viscosity shows a shear thinning behaviour as

$$\eta_{(30w.\%)} = 1.027\ \dot{\gamma}^{-0.811},\quad \eta_{(50w.\%)} = 8.99\ \dot{\gamma}^{-0.811}.$$

From these measurements it is to recognise that at an identical shear velocity $\dot{\gamma}$ the suspension with Cp = 50w.% shows a higher viscosity η than the suspension with Cp = 30w.%, consequently the break-up of the suspension jet with Cp = 50w.% will be more difficult than the suspension with Cp = 30w.% and water.

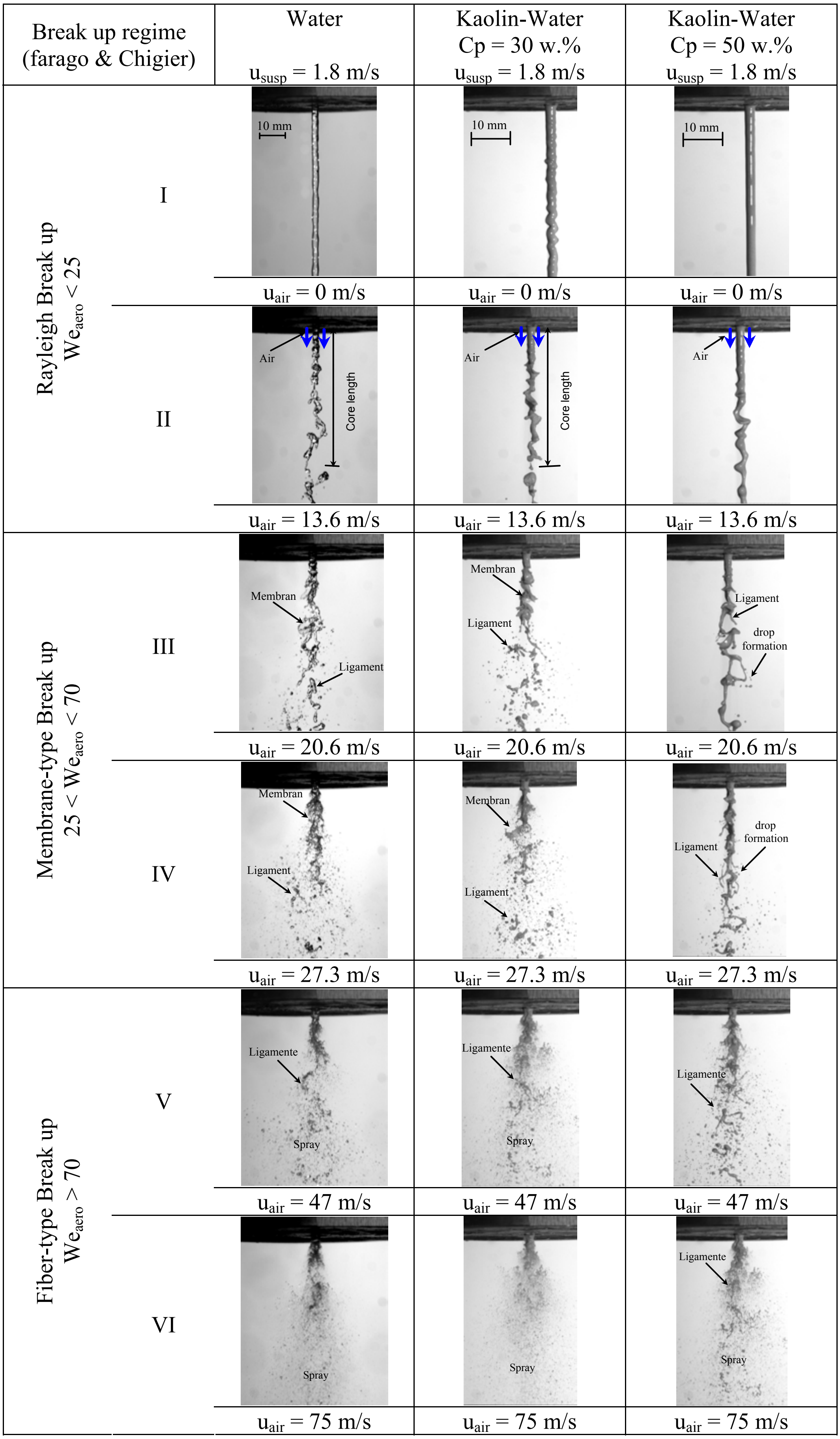


Fig. 2: Break up modes for water and suspension with a different particle loading

As a result of the shear thinning behaviour the outside area of the suspension jet shows a lower viscosity than the core area, therefore the break-up process is more extensive on the suspension/air interface, where the higher shearing dominates, than in the core of the suspension jet, where the lower shear velocity dominates.

In order to compare the results presented in this work with results published earlier it is useful to insert recent results in the (We_{aero}-Re_L)-Diagram, which derived by Farago & Chigier and has been extended by Hopfinger [3]. Each point in this diagram represents a photograph. **Fig. 3** shows an agreement with the Farago`s results regarding the upper and the lower boundaries of the break-up regimes (Rayleigh, membrane and fiber). In addition, it has beeb found here that the formation of the membrane regime takes place only for the Reynolds number ranged between ($500 \leq Re_L \leq 12000$). Depending on the Reynolds number two types of membrane formation are observed (**Fig. 4**). For lower Re_L the membrane sheet is formed from the whole liquid jet, while for higher Re_L the membrane sheet is formed only from the ligament, which peels off the main liquid jet. Within future investigation it is intended to perform additional experiments in order to explain this behaviour.

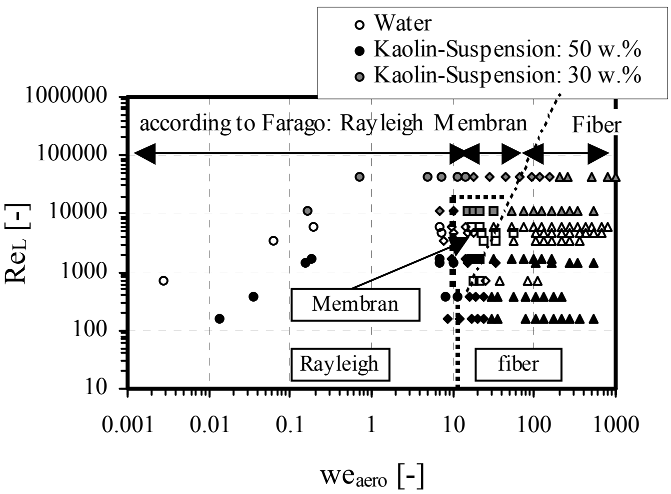


Fig. 3: Modes of water and suspension break up in coaxial air stream

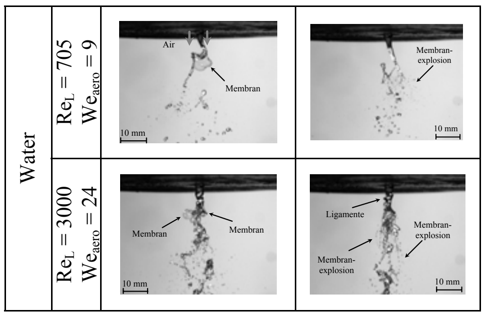


Fig. 4: Membrane break up

3.2 Correlation of Spray Data for Suspension Atomisation by a Twin Fluid Nozzle

In the pervious studies we investigated the influence of the solid particle size on the suspension atomisation by means of a twin-fluid nozzle [8]. The comparison between the resulting droplet size of the suspension atomisation and the pure liquid atomisation showed that in the velocity rang 70m/s < u_{air} < 250m/s the atomisation of suspension containing fine solid particles d_P < 50µm, as atomisation of a pure liquid, shows a monomodal drop size distribution. Furthermore at identical operation conditions (u_{air}, u_L) the resulting suspension droplet diameter is equal to the diameter of the pure liquid droplet diameter.

The present study is particularly concerned with deducing a correlating equation for the daimeter of the droplet resulting from atomisation of suspension and suspension liquid.

In the twin-fluid nozzle a high velocity gas jet (e.g. air) impinges onto the low velocity liquid jet causing the disintegration of the liquid jet into droplets. The important parameters influencing the mean droplet size are: Operating parameters, including relative velocity (u_{rel}

$= u_{air} - u_L$) and Air Liquid mass flow rate Ratio ($ALR = \dot{m}_{air} / \dot{m}_L$), physical properties of the liquid (viscosity η, density ρ and surface tension σ) and atomizer geometry as described by nozzle daimeter d_L. These parameters can be expressed in terms of dimensionless groups: Aerodynamic Weber number We_{aero}, Air liquid mass flow Ratio ALR and Ohnesorge number ($Oh = \eta_L / \sqrt{\sigma \cdot \rho_L \cdot d_L}$).

In order to describe the influence of the air velocity and the liquid velocity on the representative droplet mean diameter d_{32} in a single curve, Harari and Sher suggested to present the d_{32} as a function of the product ($We_{aero} \times ALR$)[9]. According this presentation they found that $d_{32} \approx (u_L / u_{air}^3)^n$, where n is independent of the liquid flow rate and the air/liquid velocity ratio, but rather depends on the nozzle design. In the previous reports we confirmed Harari`s results [8]. Furthermore we found the following correlation

$$d = B.(We_{aero} \times ALR)^{-0.4}, \qquad (1)$$

Where d is a characteristic droplet diameter e.g. $d_{50,3}$ or d_{32}. B is a constant, which depends on the liquid properties and the characteristic nozzle diameter. **Fig. 5** shows the droplet median diameter $d_{50,3}$ of water, glycerine/water- and CMC/water mixtures as a function of $Z_{BP} = We_{aero} \times ALR$. The relationship between the constant B and the physical properties of liquid expressed by the Ohnesorge number and the atomizer geometry as described by nozzle diameter (d_L= 3mm) is presented in **fig. 6**.

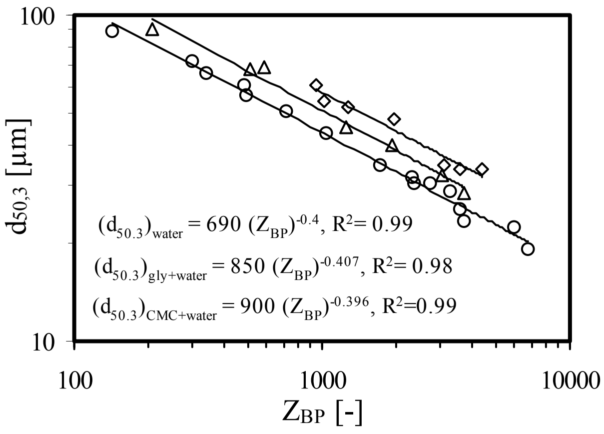


Fig. 5: Median diameter of water, Gly.+water- and CMC+water- mixture as a function of the Z_{BP}-number

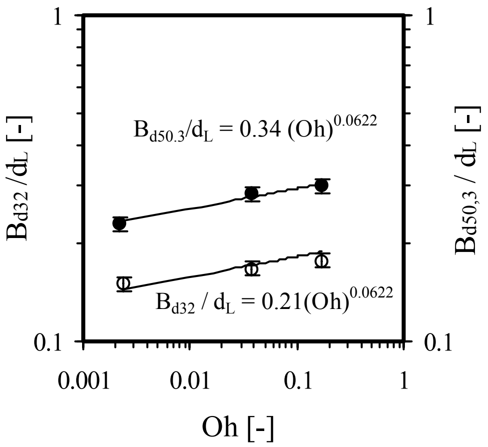


Fig. 6: constant (B/d_L) as a function of the Ohnesorge number Oh

Fig. 6 demonstrates a correlation between the ratio B/d_L and the Ohnesorge number as

$$\frac{B_{50,3}}{d_L} = 0.34 Oh^{0.0622}, \qquad (2)$$

$$\frac{B_{32}}{d_L} = 0.21 Oh^{0.0622}. \qquad (3)$$

From equation 1, 2 and 3 we indicate simple relationships of the form

$$d_{50,3} = 0.34 d_L (Oh)^{0.0622} (Z_{BP})^{-0.4}, \qquad (4)$$

$$d_{32} = 0.21 d_L (Oh)^{0.0622} (Z_{BP})^{-0.4}. \qquad (5)$$

Fig. 7 and **fig. 8** show a good agreement between the measured and the calculated characteristic droplet diameters of suspension containing small solids and liquid (within an error of$\pm 15\%$). A complete description of the particle size distribution requires two characteristics, a mean drop size and a measure of the distribution width. The ratio $d_{50,3}/d_{32}$ is generally recognized as a good measure of the width of a spray droplet size distribution [10]. For a log-normal type size distribution: $d_{32} = d_{50,3}\exp\left(-0.5\sigma_0^2\right)$. In this work the droplet size distribution is calculated according to model-independent function. The ratio between the characteristic diameters $d_{50,3}$ and d_{32} has been found to maintain a constant value that may be interpreted as a results of the independence of the width of the size distribution from operating conditions of the nozzle.

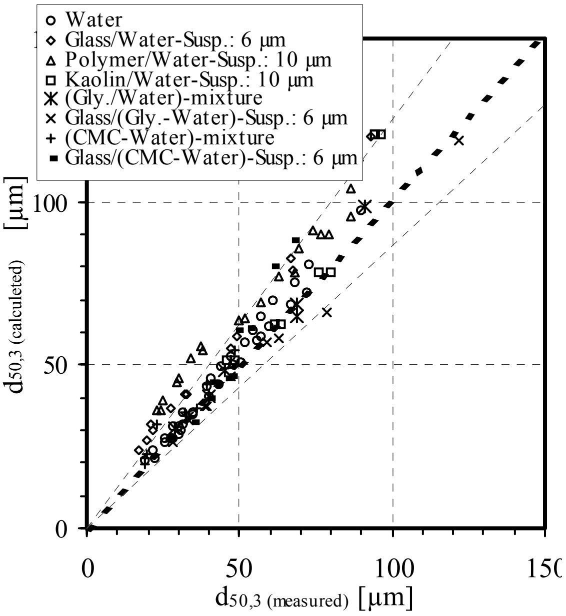


Fig. 7: Comparison between the measured liquid and suspension droplet diameter $d_{50,3}$ and the droplet diameter calculated according to Eq. 4

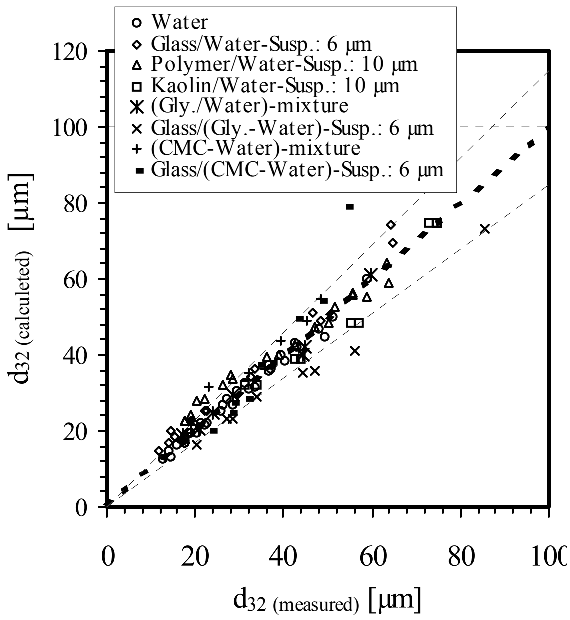


Fig.8: Comparison between the measured liquid and suspension droplet diameter d_{32} and the droplet diameter calculated according to Eq. 5

This result shows a good agreement with Shirley results for the water spray in an internally mixing nozzle ($d_{50,3}/d_{32} = 1.65$) [4].

In order to compare the results of other investigations with our correlations the droplet diameter is calculated according to different equations and compared with the in this work measured droplet size. In the **table 2** different equations are listed.

Table 2: Correlations for droplet diameter for twin-fluid atomizer

Correlations	Remarks	Ref.
$d_{32} = C.\left(\frac{\rho_L^{0.25}.\eta_L^{0.06}.\sigma^{0.375}}{\rho_{air}^{0.375}}\right).\left(\frac{\dot{m}_L}{\dot{m}_L.u_L+\dot{m}_{air}.u_{air}}\right)^{0.55}$ For our results: C = 0,12 d_L	C: constant depends on the nozzle geometry	Simmons cited in [11]
$d_{50,3} = K.d_L.\left(\left(1+\frac{\dot{m}_L}{\dot{m}_{air}}\right)\frac{\mu_L}{\mu_{air}.We}\right)^{0.5}$, $We = \frac{\rho_L . u_{rel}^2 \cdot d_L}{\sigma_L}$ For our results: Water K = 32, CMC/Water-mixture K = 5	K: constant liquid metals K = 40- 50	Lubanska [l0]
$d_{50,3} = 2600.\left(\frac{\eta_{air}}{\rho_{air}.u_{air}.(\pi.d_L)}\right)^{0.4}.\left(\frac{\dot{m}_L}{\dot{m}_{air}}\right)^{0.4}$	Valid for: $5 \le d_{50,3} \le 30$ µm	Gretzinger cited in [12]

Fig. 9 and **fig. 10** show a comparison between our results and the results of other workers listed in the table 2.

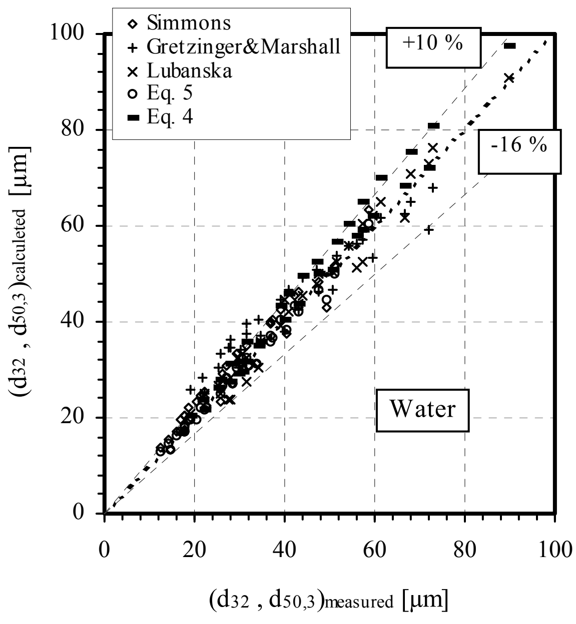


Fig. 9: Comparison between the measured water droplet diameter (d_{32}, $d_{50,3}$) and the droplet diameter calculated according to different equations

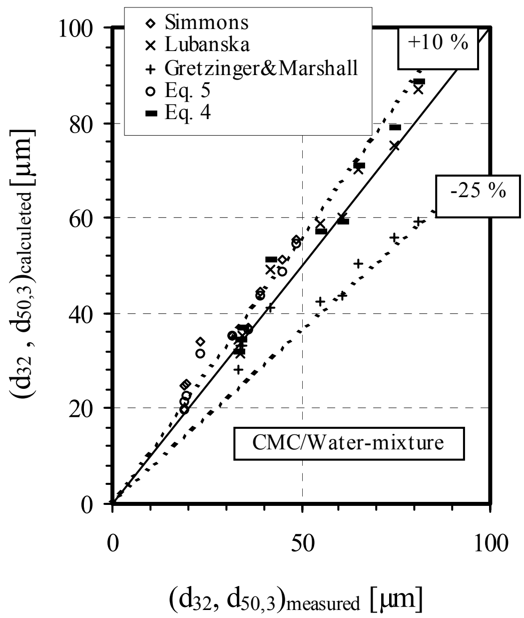


Fig. 10: Comparison between the measured CMC/water droplet diameter (d_{32}, $d_{50,3}$) and the droplet diameter calculated according to different equations

Finally it is to note that the correlation presented in this work is very similar to the Simmon equation regarding the influence of physical properties of the liquid on the droplet diameter.

4. *Summary and Conclusions*

A comparison between the atomisation of suspensions containing small solid particles and pure liquids in a twin-fluid nozzle showed that the suspension jet disintegrates in a co-axial air stream as a pure liquid jet according to three break-up mechanisms (Rayleigh, membrane, fibre type break-up). The increase of the suspension viscosity with increasing the concentration stabilizes the suspension jet. Based on the available data from liquid and model suspension atomisation an empirical formula for the droplet diameter of pure liquid and suspensions is presented: $d_{32} = 0.21 d_L \left(Oh\right)^{0.0622} \left(Z_{BP}\right)^{-0.4}$.

5. *References*

[1] Farago, Z. and Chigier, N. 1992 Atomisation & Sprays **2** 137-153
[2] Meyer, W. O. H. 1994 Experiments in Fluids **16** 401-410
[3] Lasheras, J. C., Hopfinger, E. J. 2000 Annu. Rev. Fluid Mech **32** 275-308
[4] Shirley, C. Tsai and Truc Vu, 1987 FUEL **66** 1596-1602
[5] Son S. Y. and Kihm K. D. 1998 Atomisation and Sprays, **8** 503-519.
[6] Glaser, H. W., 1989 VDI Düsseldorf
[7] Isenschmid, T., 1992 Diss. ETH Nr. 9609
[8] Mulhem, B. Fritsching, U. Schulte, G. and Bauckhage, 2001 ILASS-2001 Zurich
[9] Harari, R. and Sher, E., 1997 Atomisation and Sprays, **7** 97-113
[10] Lubanska, H 1970 JOURNAL OF METALS, 45-49
[11] Huimin Liu, 2000 Science and Engineering of Droplet: Fundamentals and Applications, William Andrew Publ., Norwich
[12] Benker, B. 1994 Diss. TU.- Claustahl