Effect of Solid Particles on Break-up of Suspension Sheets

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Studies of the effect of solid particles on spray formation by flat nozzles have shown that the presence of solid particles influences the mechanism of the liquid sheet break up. We examined this for two model suspensions (a dilute suspension and a dense suspension) by: 1.) Investigating the influence of the solid particles on the geometrical parameters of the sheet at the position of the occurrence of perforation. 2) Comparing the solid particle size with sheet thickness. From the measurements on the dilute suspension it was found that the small solid particles did not change the break-up mechanism of the liquid sheet, while the liquid sheet with large solid particles were dominated by the occurrence of perforations. However, only the suspension with a higher viscosity has shown perforations at the position when the sheet thickness was in the range of the particle diameter. From the measurements of the dense suspension it was found that increasing of the solid particle concentration stabilises the suspension sheet.

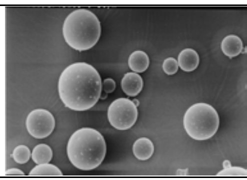
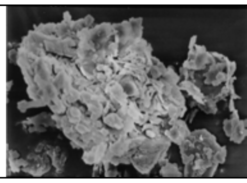
1. Introduction

Numerous researchers have investigated the perforation mechanism. The source of the perforations has been attributed to a variety of causes such as suspended solid particles, liquid droplets, air bubbles and/or turbulence [1]. Dombrowski and Fraser [2] 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 marked effect and cause perforation of the sheet. Butler et al. [3] studied the disintegration of the dilute emulsion sheets. They found that the perforations did not appear at the position where the particle diameter was equal to the sheet thickness. They assumed that the emulsion particles interact with the local perturbations within the flow. These perturbations grow causing a hole in the sheet. Glaser [4] studied the break up of suspension sheet containing different solid particles. He found that solid particles with a little relative density affect the sheet stability when the sheet thickness is thinner than the solid particle size. While the acceleration of the solid particles with a large relative density achieve the instability and the turbulence of the suspension sheet.
This study aims to investigate the influence of the solid particles on the disintegration and on the geometrical parameters of the suspension sheet forming from a flat nozzle. In addition, the relationship between the thickness of the liquid sheet at the position of the perforations and the solid particle size were investigated.

2. *Experimental Set-up*

In order to determine the effect of suspended solid particles on the break-up of the liquid sheet different model suspensions based on water and glycerine-water mixtures with various suspended glass and Kaolin particle fractions were atomized by means of a flat jet nozzle. Table 1 shows the properties of suspensions used. **Fig. 1** shows a schematic illustration of the experimental set-up and the flat nozzle. The suspension jet discharges from a flat spray nozzle (Spraying systems: type 1/4P-5040) with the diameter D = 3,6mm. Photographs of the liquid sheet are taken with CCD-camera immediately downstream of the nozzle. A pressure transducer measures the liquid pressure at the nozzle.

Table 1: Properties of suspensions used

<table>
<tr><td colspan="6">Model suspensions</td></tr>
<tr><td colspan="2">Suspension liquid</td><td colspan="4">Solid particle</td></tr>
<tr><td>Water</td><td>ρ_L = 1000 kg/m³
σ = 0.072 N/m
η_L = 0.001 Pa.s</td><td rowspan="3">Glass</td><td rowspan="2">ρ_P = 2500 kg/m³
Cp = 7 Vol.%
d_P = 6, 56, 94, 228μm</td><td rowspan="3">Kaolin</td><td rowspan="2">ρ_P = 2600 kg/m³
Cp = 7 - 30 Vol.%
d_P = 10 μm</td></tr>
<tr><td>glycerine/water
(60 % + 40 %)</td><td>ρ_L = 1160 kg/m³
σ = 0.0564 N/m
η_L = 0.0108 Pa.s</td></tr>
<tr><td>glycerine/Water
(70 % + 30 %)</td><td>ρ_L = 1190 kg/m³
σ = 0.0528 N/m
η_L = 0.025 Pa.s</td><td></td><td></td></tr>
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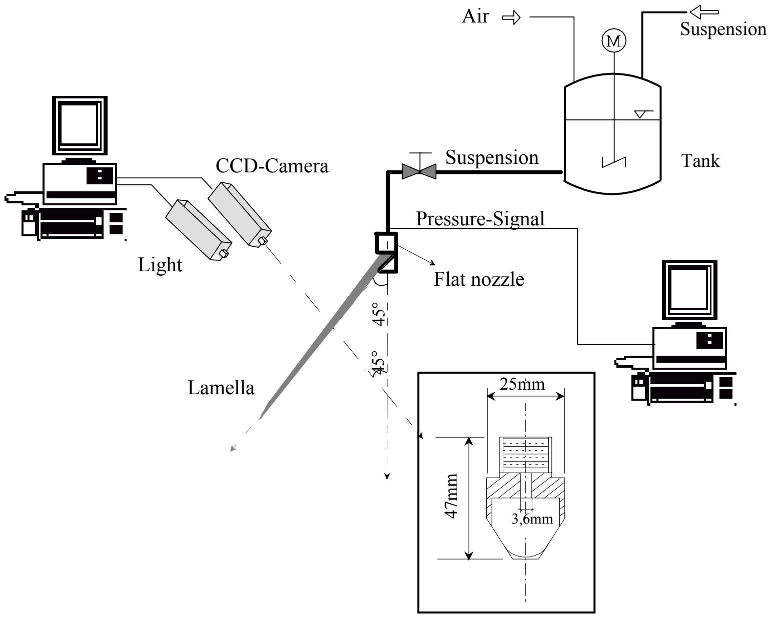


Fig. 1: Experimental set-up and the used flat nozzle (spraying systems ¼P-5040)

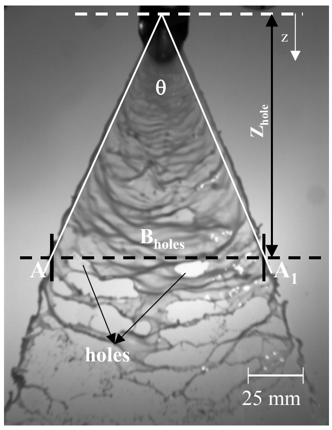


Fig. 2: Geometrical parameters of the liquid sheet

More than 30 photographs were taken at each operating condition. The width of the liquid sheet B_{hole} and the length of the sheet Z_{hole} at the position of the occurrence of perforation were measured from the photographs (s. **Fig. 2**). Further more the sheet angle θ and the sheet thickness at the position of the perforation δ_{hole} were calculated from the following equations respectively

$$\theta = 2 \cdot \arctan\left(\frac{Z_{hole}}{0.5 \cdot B_{hole}}\right), \qquad (1)$$

$$\delta_{hole} = \frac{\dot{m}_L}{\rho_L \cdot u_L \cdot B_{hole}}. \qquad (2)$$

Each point in the following diagrams represents the average of 30 measurements.

3. Results and Discussions

Fig. 3 shows photographs of the break up process of a pure liquid and dilute suspension sheets. The photographs demonstrate that the pure liquid sheet as well as the suspension sheet break up into drops according to the following stages: 1.) Development of asymmetric waves, which were induced by aerodynamic forces acting on the air/liquid interface [5]. 2.) Formation of perforations (holes), which grow in the sheet by acting of the surface tension causing a break up of the sheet into ligaments. 3) Finally the surface tension forces lead to disintegrate the ligaments into drops. In addition **Fig. 3** shows that the formation and interaction of perforations in the sheet clearly dominate the break up process of the liquid sheet containing solid particles. The comparison between the photographs of suspension sheets containing different solid particle fractions shows that the increase of the solid particle size changes the position (Z_{hole}) and the number of perforations formed in the liquid sheet. While the liquid sheet containing small particles d_P = 6µm forms holes and disintegrates far from the nozzle, the liquid sheet containing large particles d_P = 228µm formed holes and disintegrates into ligaments and drops near to the nozzle. This is more evident for p_{rel}=0,4 but also recognizable in case of p_{rel}=1,4bar

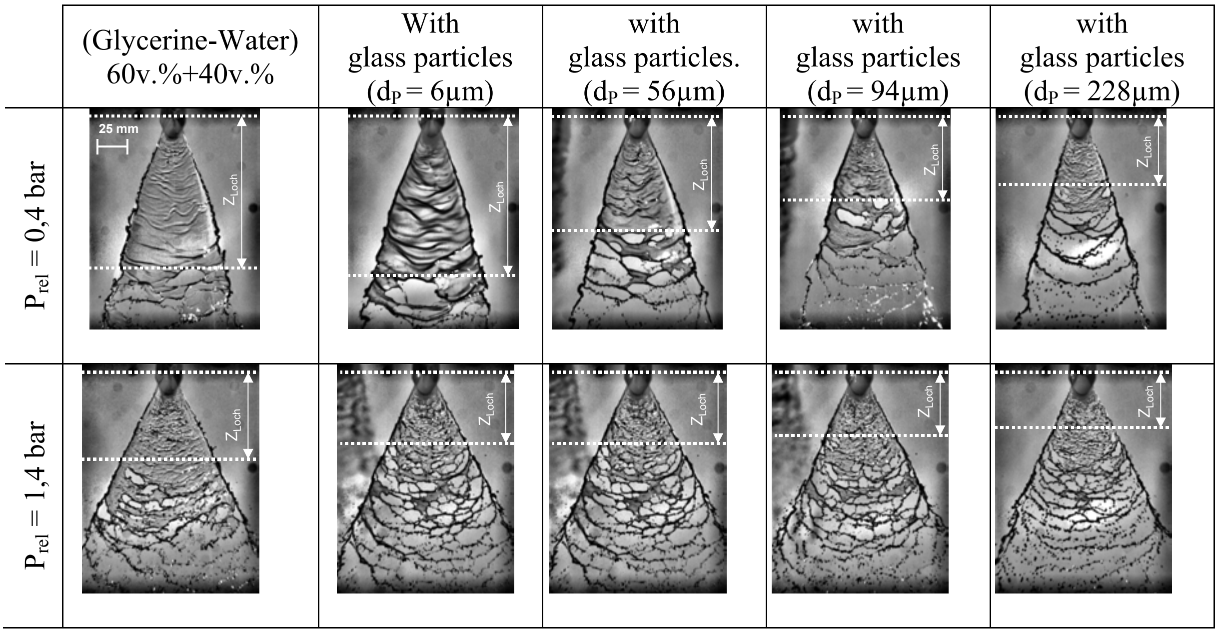


Fig. 3: Photographs of dilute suspension sheets with different solid particle size and a constant solid concentration Cp = 7 v.%

3.1 Influence of Solid Particle Size on the Geometrical Parameters of the Liquid Sheet

From the measurements of various liquid sheets and dilute suspension sheets it was found, that the geometrical parameters of the liquid sheet will be influenced by the following parameters:

$$(\theta\ ,\ Z_{hole}\ ,\ \delta_{hole}) = f(\eta_L\ ,\ \rho_L\ ,\ d_P\ ,\ \rho_P\ ,\ \sigma\ ,\ P_{rel}). \qquad (3)$$

Fig. 4 shows that the sheet angle decreases with increasing the liquid viscosity (η_L) and with decreasing the relative pressure (P_{rel}), while the increase of the solid particle size does not affect the sheet angle. This behaviour is expected because a small loading of the solid particle (Cp = 7v.%) shows a little effect on the suspension viscosity.

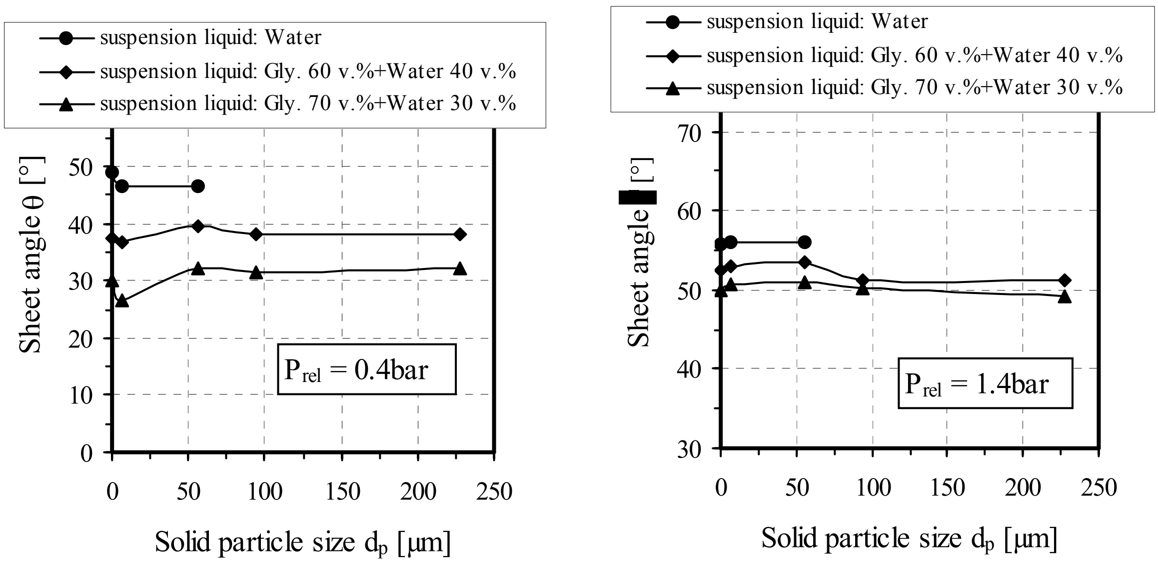


Fig. 4: Sheet angle of a dilute suspension as a function of the solid particle size at two different pressures

Fig. 5 shows that the length of the sheet at the position of the perforation Z_{hole} increases with increasing the liquid viscosity (η_L) and with decreasing the relative pressure (P_{rel}). However, the length of the sheet Z_{hole} decreases with increasing the solid particle size in the liquid sheet. The strong sedimentation effect has precluded the experiments with large glass particles suspended in the water.

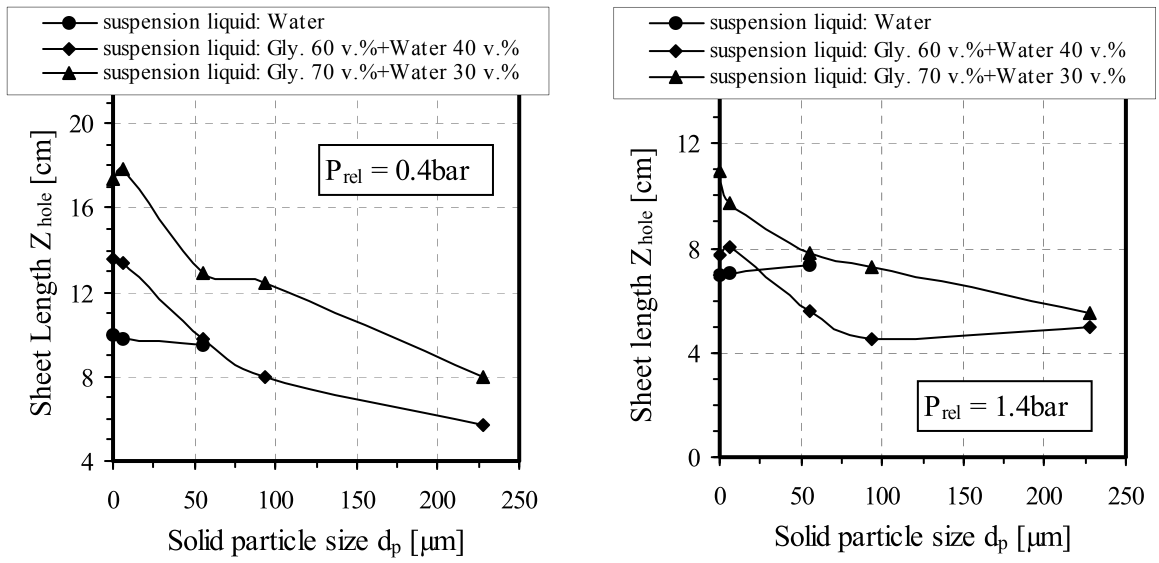


Fig.5: Sheet length at the position of the perforation for a dilute suspension as a function of the solid particle size at two different pressures

From the photographs it was found that the break up of the liquid sheet containing solid particles is dominated by the occurrence of perforations (s. **Fig. 3**). At a constant pressure the occurrence of perforations seems to be related to the size of solid particles in the liquid sheet. In order to study this relationship the solid particle size has been compared with the sheet thickness at the position of the perforation δ_{hole}. **Fig. 6** shows generally that the sheet thickness δ_{hole} increases with increasing the solid particle size and with decreasing the liquid viscosity (η_L) also with increasing the relative pressure (P_{rel}). This behaviour indicates that the solid particles interact with the local perturbations within flow. These perturbations grow causing a hole in the sheet [3]. Here is to note that local perturbations will become higher with lower liquid viscosities (η_L) and by increasing the sheet velocity (increasing the relative pressure P_{rel}). In other words the local perturbations increase with increasing the liquid Reynolds-number Re_L. As higher Re_L as stronger are the local perturbations in the liquid sheet.

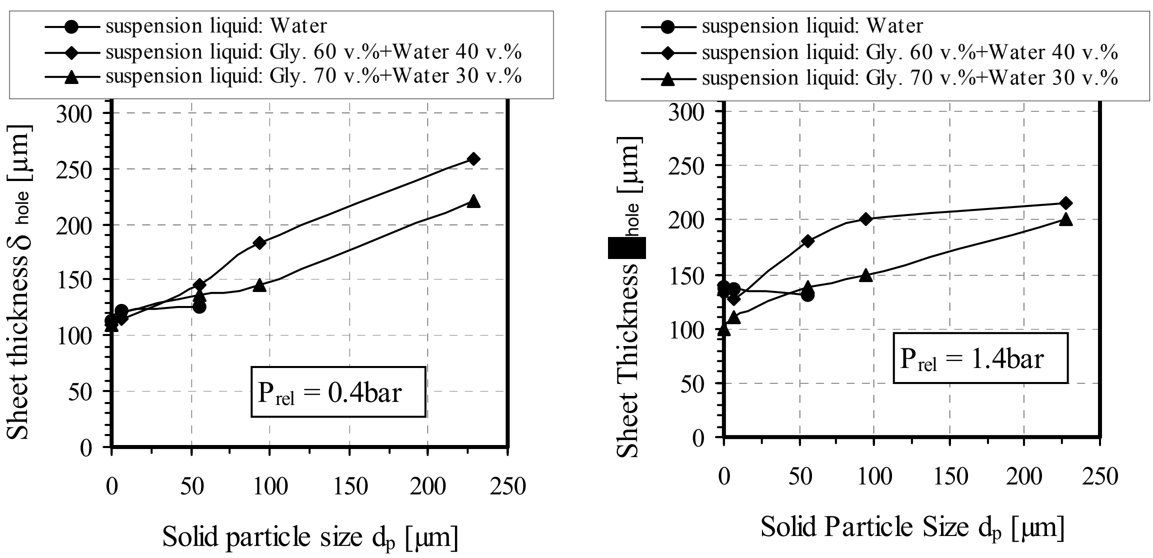


Fig. 6: Sheet thickness δ_{hole} at the position of the perforation for a dilute suspension as a function of the solid particle size at two different pressures

In this work the measurements of suspensions based on the (Gly.70 v.% + Water 30 v.%)-Mixture have shown that the increase of the pressure P_{rel} has little influence on the sheet thickness δ_{hole}. This behaviour can be explained as a result of weak local perturbations in the liquid sheet with a lower Reynolds-Number Re_L. Consequently one can write

$$\delta_{hole} = f(d_P). \tag{4}$$

A comparison between characteristic solid particle diameters ($d_{50,3}$, $d_{90,3}$) and the sheet thickness δ_{hole} of suspensions based on (Gly.70v.%+Water 30v.%)-Mixture and with solid particles d_P = 56 and 94µm at different pressures shows that the perforations in the sheet appear at the position when the sheet thickness is more or less equal to the particle diameter $d_{90,3}$ (s. **Fig. 7**). The small solid particles (d_P = 6µm) do not show a clear influence on the position of the perforations, while the larger solid particles (here represented by $d_{90,3}$) seem to dominate the process of perforation.

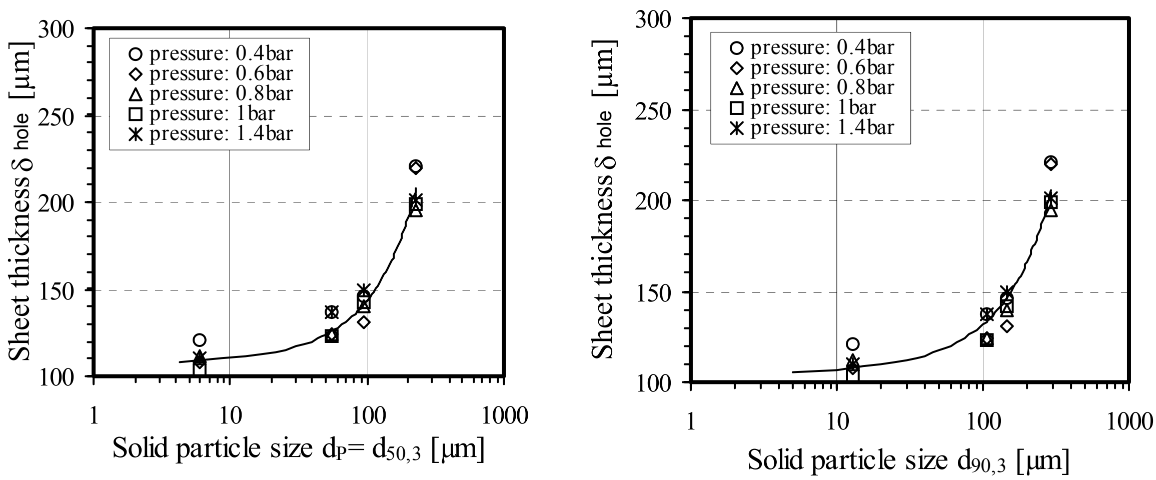


Fig 7: Sheet thickness δ_{hole} at the position of the perforation for a dilute suspension based on (Glycerin70v.%+Water30v.%)-Mixture at different pressures as a function of two representative solid particle diameters

In the case of suspension with d_P= 228µm the sheet shows perforations where the thickness δ_{hole}. < $d_{50,3}$; $d_{90,3}$. We believe this behaviour is a result of the sedimentation of the large particles in the tank. At least we observed after some experiments especially for suspensions with large particles that a certain amount of the large particles of the collective are still at the bottom of the tank.

3.2 Influence of Solid Particle concentration Size on the Break up of the Liquid Sheet

In the case of a pure liquid sheet it was found that an increase in liquid viscosity reduces the growth rate of the aerodynamic instabilities and increases the wavelength of maximum growth rate. In other words the viscous forces influence the stability of the sheet.
In the suspension the interaction between the solid particles grows with higher solid particle concentration. This also lifts the suspension viscosity and consequently it is to expect that the solids concentration affects the sheet break up as well as its geometrical parameters.

In order to study the influence of the solid particle loading on the sheet break up various suspensions are studied. **Fig. 8** shows photographs of the break up of water and dense suspension sheets. In the experiments the solid particle concentration is changed between 7 v.% and 30 v.%, while the solid particle size hold on d_P = 10 µm. The photographs of water sheet and suspension sheet with solid particle concentration Cp = 30 v.% show a clear influence of the solid particle concentration on the break up as well as on the geometrical parameters of the sheet. Increasing of the solid particle concentration damps the development of asymmetric waves in the sheet. In addition the sheet angle decreases with increasing the solid particle concentration. The position of the perforations increases with increase the solid particle concentration in the suspension.

Finally it is to note that the photographs of the liquid sheet with solid particle concentration 10 v.% < Cp < 30 v.% have shown that the solid particles tend to agglomerate in liquid sheet. This behaviour led to a significant scattering of the results in the measurements of the position of the perforations in the suspension sheets.

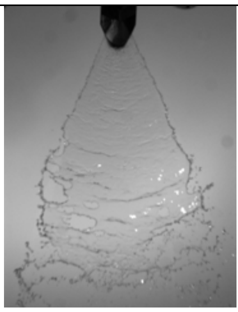
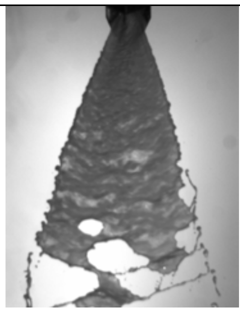
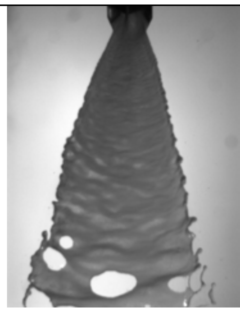
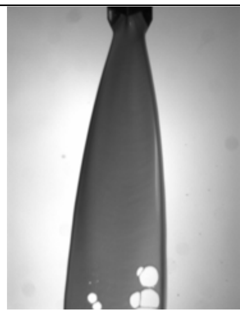
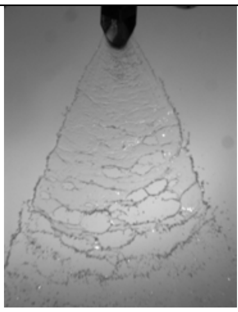
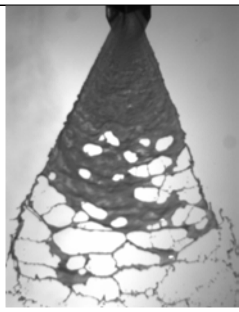
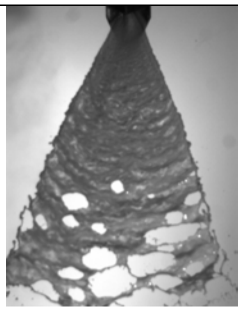
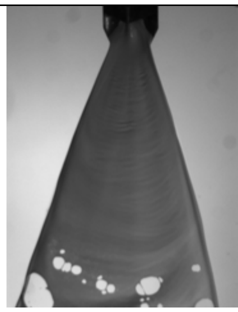
	suspension liquid water	with Kaolin particles Cp = 17 v.%	with Kaolin particles Cp = Cp= 23 v.%	With Kaolin particles Cp = 30 v.%
P_{rel} = 0.4 bar				
P_{rel} = 0.8 bar				

Fig. 8: Photographs of suspension sheets with different solid particle concentration and a constant solid particle size d_p = 10µm

4. *Summary and Conclusions*

The effect of the solid particle size and particle loading on the break up of the suspension sheet was investigated through the visualization of the disintegration of model suspension sheets formed from a flat spray nozzle. Various model suspensions based on water and mixtures of glycerine/water with different solid particle size and particle loading was atomized. From the measurements of the dilute suspension it was found that the small solid

particles d_P = 6μm did not change the break up mechanism of the liquid sheet, while the liquid sheets with larger solid particles (d_P = 56, 94, 228μm) were dominated by the perforations. The position of the perforation seems to be influenced by a number of parameters such as ρ_L, ρ_P, η_L, σ, u_L and d_P. However, only suspensions with a high liquid viscosity have shown perforations at the position when the particle diameter was equal to the sheet thickness $\delta_{hole} = d_{90,3}$. From the measurements of the dense suspension it was found that the increasing of the solid particle concentration stabilises the suspension sheet.
In the next future we plane to perform more experiments with other model suspensions in order to validate the results of this work.

5. References

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