PHOTOGRAHIC OBSERVATION OF BREAK-UP OF HOLLOW CONE SUSPENSION SHEET

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ABSTRACT

The influence of the solid particle size, concentration and density as well as the effect of the carrier liquid on the break-up of a hollow cone suspension sheet was studied experimentally. The photographs of the sheet break-up have shown that the solid particles have an influence on the sheet break-up and its parameters. Increasing of the solid particle concentration leads at first to increase the break-up length of the suspension sheet compared with the pure carrier liquid sheet, further increasing of the concentration leads to decrease the break-up length. The effect of the concentration is influenced by the carrier liquid. It seems that there is a critical concentration at which the break-up length becomes a maximum value. The solid particle size and density affect the perforation mechanism in the dilute suspension sheet. In this case solid particles with high relaxation time (large diameter or high density) can not follow the turbulent fluctuations in the liquid sheet that leads to enlarge the velocity difference between the particles and the liquid. Accordingly, the perforation mechanism is promoted by the solid particles.

INTRODUCTION

Atomization of suspension is a unit operation in chemical engineering, where a suspension is transferred into a system of dispersed drops, which depending on the operating conditions might be pure carrier liquid drops, dried solid particles or suspension drops. By atomization of liquid containing solid particles (suspension) it is important to minimize the danger of blockage of the nozzle. A type of nozzle which has found widespread use in suspension atomization is the hollow cone nozzle, wherein the liquid is injected through tangential passages into a swirl chamber, from which it emerges with both tangential and axial velocity components to form a thin conical sheet at the nozzle exit. This sheet rapidly attenuates, finally disintegrating into ligaments and then into drops [1,2]. Depending on the injection pressure, liquid properties and the geometry of the nozzle the break-up of liquid sheet into drops can be divided into three mechanisms (contraction, aerodynamic waves, perforation and turbulence) [3]. In industrial applications the swirl nozzle works according to the aerodynamic waves or the turbulence mechanisms, wherein the liquid cone sheet breaks up into drops with small diameter. The Break-up mechanism and the influence of the injection pressure, liquid properties and nozzle geometry on the sheet parameters (break-up length, spray cone angle and sheet thickness) and on the resulted drop size in the spray have been published e.g. in [1,4,5,6].

In contrast to the break-up of a hollow cone liquid sheet there is a lack in the theoretical and experimental works dealing with the break-up of suspension sheet. Dombrowski and Fraser [3] 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 [8] investigated the break up of suspension sheets containing different solid particles. He found that solid particles with a little relative density affects the sheet stability if the sheet 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. Dahl [7] analysed the suspension flow inside a swirl nozzle. Dahl found that the cyclone-theory can be used to calculate the friction losses and the velocities in a swirl nozzle. Further more his measurements showed that in the case of lime suspension the side friction is comparable with it for the pure liquid for low Reynolds numbers, while it becomes a high value than that in the case of pure liquid at high Reynolds numbers. Parthasarathy [9] used a spatial stability analysis to study the nature of unstable wave growth in the case of dilute and dense slurry sheet containing small particles. The calculations of Parthasathy showed that the presence of particles reduces the disturbance growth rate without affecting the dominant wavenumber, in the case of dilute slurry. For viscoelastic fluids (dense slurry), the Deborah number plays an important role in the wave growth. Thus, viscoelasiticity acts as a destabilizing agent. Both the drop sizes and the break-up length is expected to be smaller, compared to the Newtonian fluid, under the similar conditions. Shimizu and el.at.[11]

investigated the influence of abrasive particles on the jet structure. His results showed that small abrasive particles tend to suppress the disintegration of the jet, whereas larg abrasive particles tend to promote jet break-up. The effect of abrasive particles on the jet structure are clear when using abrasive of high density. When the density of the abrasive is high, the effects of abrasive concentration on the jet structure are more evident. S. Schütz and el.at [10] concerned the semi empirical Carreau-Yasuda-Model to describe the flow behaviour of suspension in a mathematical-physical model to calculate the resulted mean droplet diameter in suspension spray produced by a hollow-cone nozzle. A good agreement between the calculation and the measurements of two different lime suspensions was reported.

This study aims to investigate the influence of the solid particle concentration, size and density on the break-up of the hollow cone suspension sheet based on different Newtonian carrier liquids.

EXPIRMENTAL SETUP

In order to determine the effect of suspended solid particles on the break-up of the hollow cone liquid sheet different model suspensions based on water, Ethanol/water-mixture and glycerol/water-mixture with various suspended Clay, glass, polymer and siliciumcarbide particle fractions were atomized by means of a hollow cone nozzle (Spraying systems: QUICK-WHIRLJET-DÜSE QA-5). The nozzle has the diameters: d_{out}= d_{inlet}=3.6mm, $d_{chamber}$=11mm. **Table 1** shows the properties of suspensions studied.

Table1: Model suspensions and the goals of the experiments

Suspension	Cp v.%	dp µm	Goal
Clay-water (ρ_L= 1g/cm³, η_L= 1mPa.s, σ_L= 72mN/m)	0 - 30	10	- Effect of solid particle concentration on the sheet parameters. - Effect of carrier liquid properties on the sheet parameter.
Clay-(20v.%Ethanol+80v.%water) (ρ_L= 0.966g/cm³, η_L= 1,84mPa.s, σ_L= 44,86mN/m)			
Clay-(75v.%Glycerol-25v.%water) (ρ_L= 1.188g/cm³, η_L= 57,4mPa.s, σ_L= 53,58mN/m)			
Siliciumcarbide-(75v.%Glycerol-25v.%water) (ρ_L= 1.188g/cm³, η_L= 57,4mPa.s, σ_L= 53,58mN/m)			
Glass-(75v.%Glycerol-25v.%water)	5	35 - 95	- Effect of solid particle size on the sheet parameter.
Polymer-water	5	53	- Effect of solid particle size on the sheet parameter.
Siliciumcarbid-water			

Photographs of the hollow cone suspension sheet are taken with CCD-camera downstream of the nozzle. A pressure transducer measures the suspension pressure at the nozzle inlet. The pressure is changed up to 2.2bar. The suspension flow rate is determined by measuring the weight by time. **Fig. 1** shows a schematic illustration of the hollow cone nozzle and the studied parameters (angel θ/2, perforation distance Z_{hole} and break-up length Z) of the hollow cone suspension sheet.

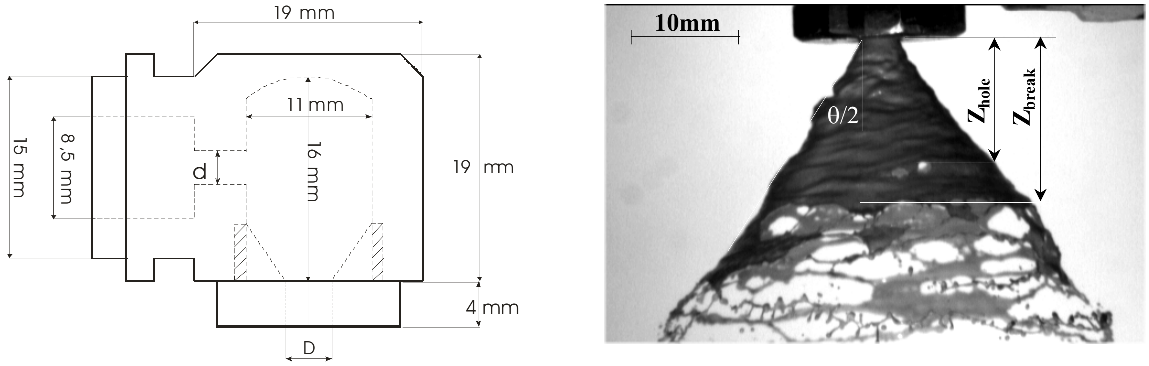
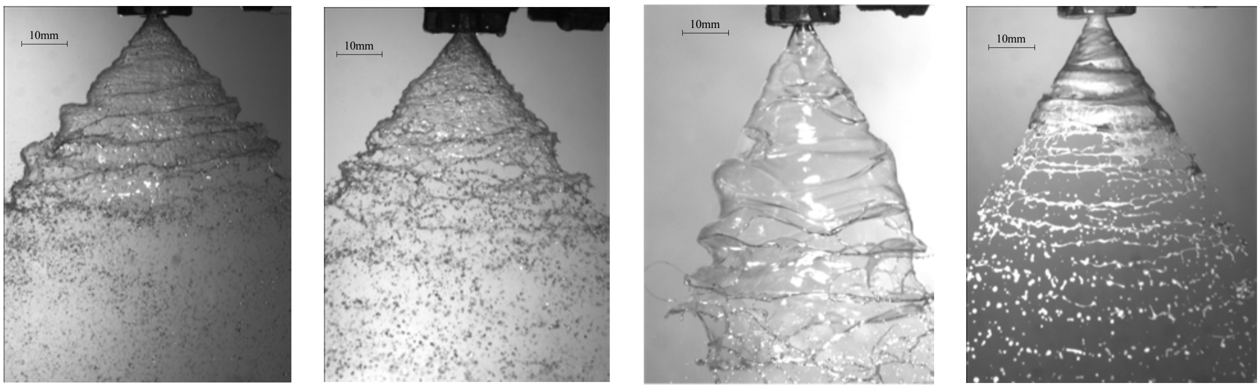


Fig. 1: Hollow cone nozzle (spraying systems: AQ-5) and the studied parameter of the hollow cone suspension sheet

RESULTS AND DISCUSIONS

Influence of solid particle concentration on the sheet parameters

Fig. 2 shows photographs of the break-up process of the 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 photographs show that the hollow cone liquid sheets will disintegrate into ligaments and drops according to the aerodynamic waves.



Water	Ethanol/water-mixture	Glycerol/water-mixture	Clay/water-suspension Cp = 30v.%

Fig. 2: Photographs of the hollow cone sheet of different carrier liquid and a suspension based on water at an injection pressure p_{rel} = 1.2bar

For a given nozzle geometry the liquid flow rate injected from the nozzle and the formation of the hollow cone sheet is strongly influenced by the injection pressure and the friction losses occurred in the nozzle. The increase of the liquid viscosity leads to increase the losses inside the nozzle, which leads to decrease the tangential velocity of the liquid consequently the diameter of the air core in the nozzle decreases and as a result the liquid flow rate increases. On the other hand the spray cone angle (θ) decreases as a result of decreasing the tangential velocity component. The increase of the liquid flow rate and the decrease of the spray cone angle with increasing the liquid viscosity (see table1) is shown in **fig. 3** and **fig. 4** respectively. **Fig. 5** shows that the increase of the liquid viscosity from 1mPa.s in the case of pure water to 57.4mPa.s in the case of Glycerol/water-mixture leads to increase the break-up length of the sheet, which can be explained as a result of the stabilizing effect of the liquid viscosity on the break-up of the liquid sheet [1], while in the case of Ethanol/water-mixture (η_L = 1.84mPa.s) the break-up length becomes shorter. In this case the positive influence of the decreasing of the surface tension on the break-up length (shorter break-up length) covers the negative influence of increasing the liquid viscosity (longer break-up length). Anyway these results show a good agreement with published results e.g. by Lefebvre [1].

By adding solid particles to the carrier liquid the flow behaviour will change, it becomes shear thinning (see **fig. 6**) and the viscosity of the suspension will increase with increasing the particle concentration. Therefore it is also to expect that the increase of the solid particle concentration leads to increase the losses and consequently to increase the flow rate and decrease the spray cone angle. **Fig 3** and **fig. 4** show that the increase of the solid particle concentration in the suspension based on water to Cp= 30v.% leads to increase the suspension flow rate injected from the nozzle and to decrease the spray cone angle. Noteworthy it is the lightly increase of the flow rate, epically at high injection pressures, and the strongly decrease of the spray cone angle by increasing the solid particle concentration to 30v.%. This behaviour of the suspension flow rate is to explain as a result of the shear thinning behaviour of the suspension, where the suspension shows a high viscosity at low shear rate (e.g. at pressure 0.2bar, where the suspension flow rate is comparable with the flow rate of glycerol/water-mixture with 57.4mPa.s). For high shear rate (e.g. at p_{rel} = 2bar) shows the suspension low viscosity and therefore low flow rate (smaller liquid outlet). The strongly influence of the solid particle concentration on the spray cone angle is a result of the decrease of the tangential velocity of the suspension in the swirl chamber of the nozzle. The decrease of the tangential velocity is controlled by the pressure losses inside the nozzle, which increase with increasing the solid particle concentration in the suspension (high side friction in swirl chamber) [4].

Fig. 5 shows that the increase of the solid particle concentration to 30v.% leads to decrease the break-up length, on the other hand it seems to be that the break-up length is independent on the injection pressure. This behaviour might be explained as a result of dewetting of solid particles by attenuating of suspension sheet [3], or as a result of the destabilizing affect of the strong viscoelasiticity of the high concentrated suspension [9].

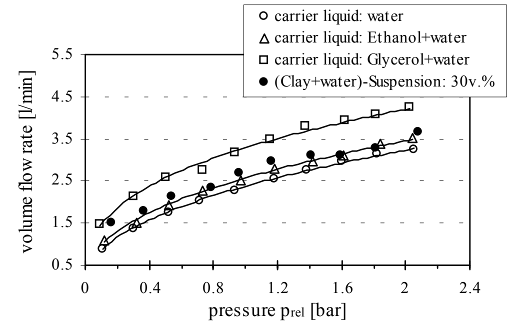


Fig. 3: Flow rate as a function of the pressure

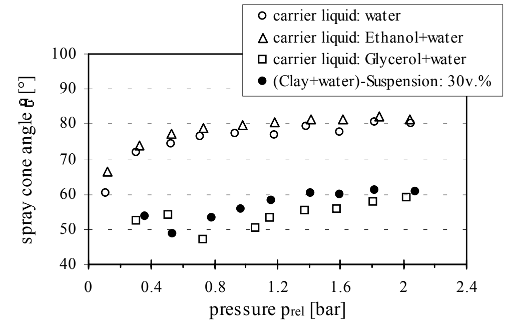


Fig. 4: Spray cone angle as a function of the pressure

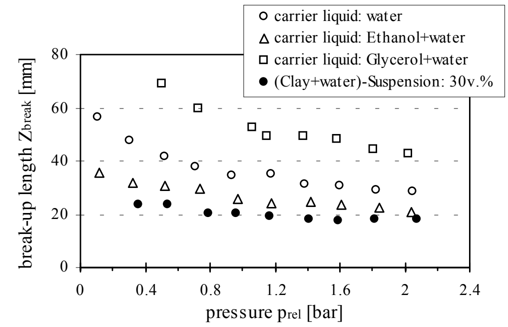


Fig. 5: Break-up length as a function of the pressure

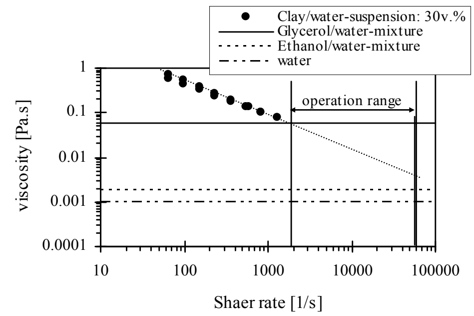


Fig. 6: Liquid and suspension viscosity as a function of the shear rate

In the case of suspension based on Ethanol/water-mixture as well as suspension based on Glycerol/water-mixture and with different solid particles (Clay, Siliciumcarbide) it was observed that the increase of the solid particle concentration to Cp = 15v.% leads to increase the break-up length, while the suspension flow rate do not change. With further increasing of the solid particle concentration the break-up length starts to decease (see **fig. 7-a, 7-c, 7-d**). In the case of suspension based on water a very light increase of the break-up length was observed for the solid particle concentration (Cp = 4v.%), and a further increase of the concentration leads to decrease the break-up length (**fig. 7-b**). It seems that there is a critical concentration at which the break-up length of the sheet becomes a maximum value. This value depends on the carrier liquid. Parthasarathy [9] reported in his study that the presence of small particles decreased the disturbance rate without affecting the dominant wavenumber. In this case the particles dissipate the energy of the disturbances by their drag; thus, they have a stabilizing effect on the liquid. Unfortunately, the results presented here are the first experimental studies of slurry sheet break-up, which confirms the theoretical study presented by parthasarathy [9]. Anyway the similar effects of the solid particles were presented by Shimizu [11] in the case of suspension jet.

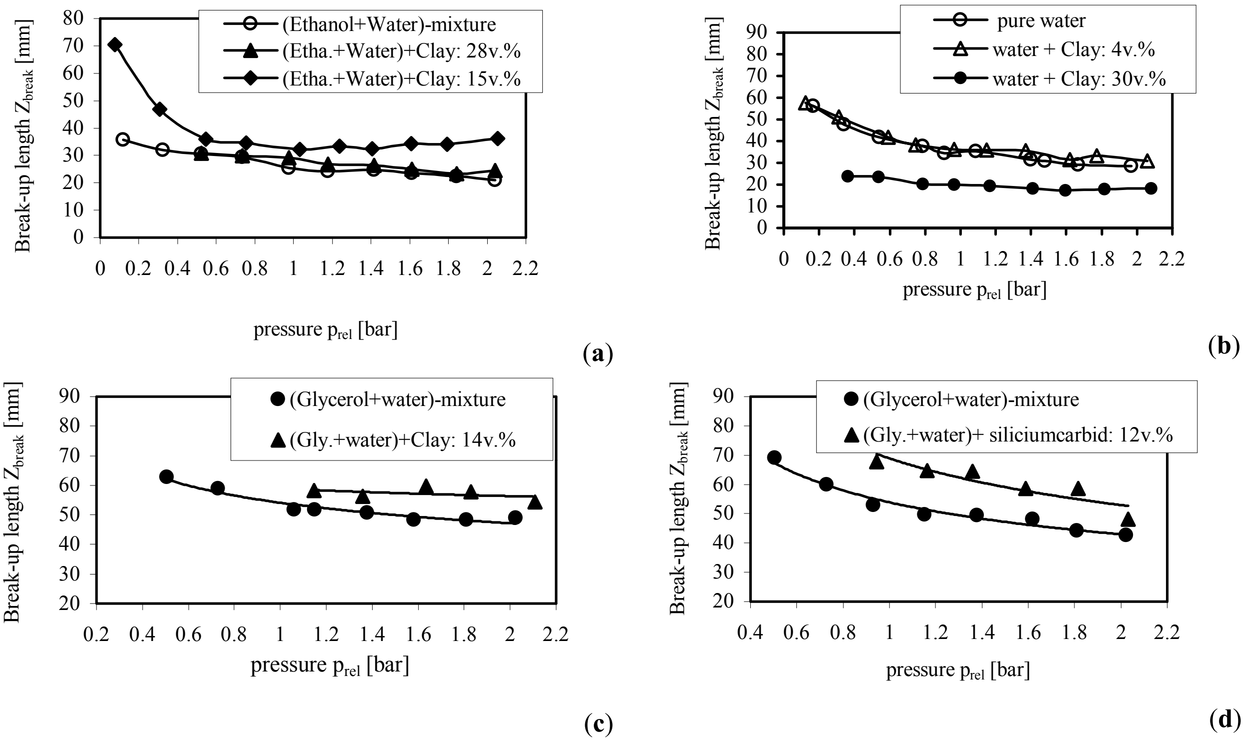


Fig. 7: The break-up length Z_{break} as a function of a pressure for different carrier liquids and different concentration

Influence of the solid particle size and the particle density on the sheet parameters

The influence of the solid particle size on the break-up 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 (Cp=5v.%) no significant influence of the solid particle on the suspension flow rate, on the spray cone angle and on the break-up mechanism was observed (see **fig. 8**). The only influence of the solid particle size was on the perforation distance Z_{hole} . The distance Z_{hole} decreased with increasing the glass particle size (fig. 8).

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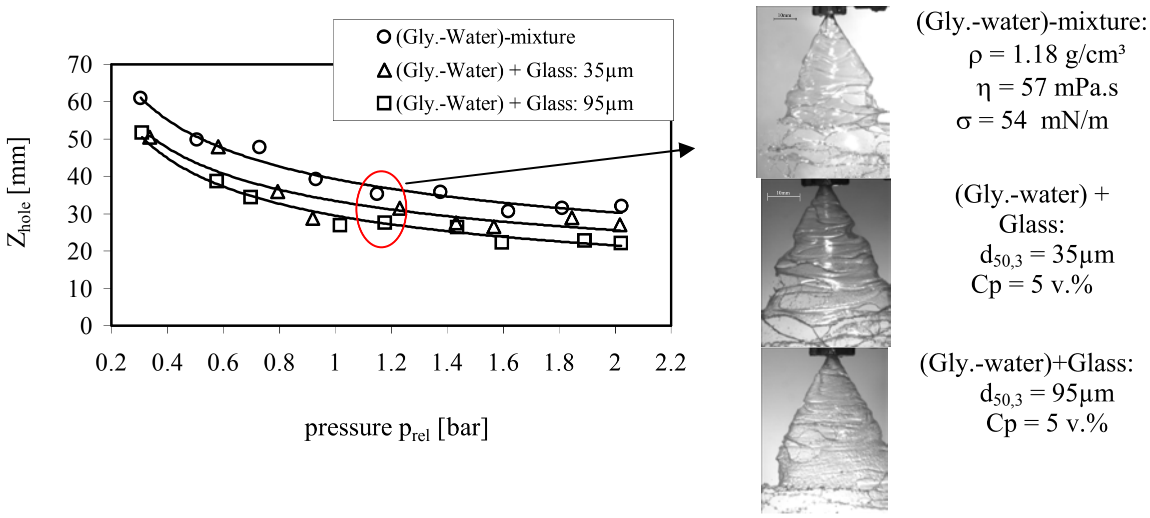

Fig. 8: Sheet length at the position of the perforation for a dilute suspension (Cp = 5v.%) based on Glycerol/water-mixture and with glass particles different size as a function of the pressure.

In order to compare the sheet thickness at the position Z_{hole} with the solid size the sheet thickness was 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 [8] that the suspension sheet containing high density solid particles shows perforations, where the sheet thickness is much thicker than the solid particle size. **Fig. 9** shows the calculated sheet thickness at Z_{hole} for the two glass suspensions and for the carrier liquid.

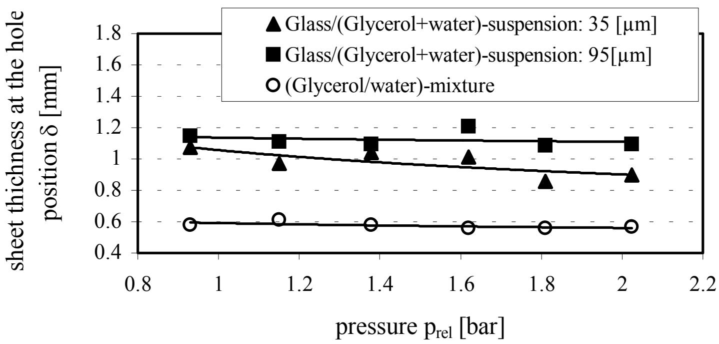

Fig. 9: Sheet thickness at the hole position as a function of the injection pressure

Fig. 10 shows the perforation distance as a function of the pressure for two dilute suspensions (Cp = 5v.%) containing two different solid particles (polymer: 1.1g/cm, dp = 53µm and siliciumcarbide: 3.2 g/cm³, dp = 53µm) and based on water.

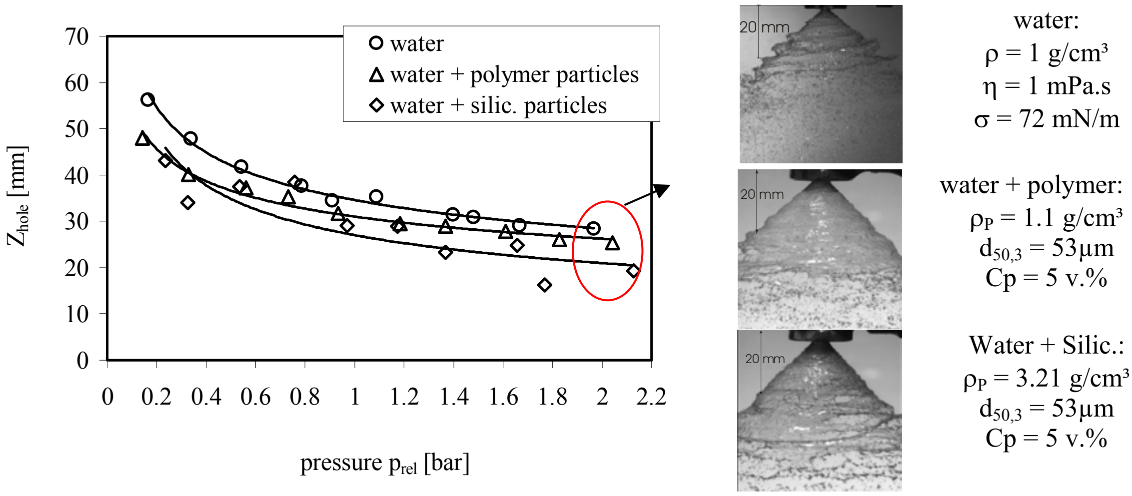

Fig. 10: Sheet length at the position of the perforation for a dilute suspension (Cp = 5v.%) based on water and with polymer particles and with siliziumcarbid particles as a function of the pressure.

Fig. 8 and **Fig. 9** show that the increase of the solid particle size and the increase of the solid particle density leads to decrease the perforation distance Z_{hole} in comparison to Z_{hole} of the carrier liquid. Anyway it is no clear relationship between the sheet thickness and the solid particle size. Shimizu and el.at [10] investigated the accelerations of the spheres abrasive particles suspended in water and having different densities and diameters. The results showed that the velocity difference between the water and the particles with the highest density and relative large diameter is much higher than the velocity difference between the other particles (lower density and smaller diameter) and water. Accordingly, the turbulent motion of the water phase is enlarged and jet break-up is promoted by the particles with the highest density and large diameter. This effect of the abrasive particle on the water jet break-up seems to be the similar effect of the solid particles on the perforation mechanism in the case of suspension sheet.

CONCLUSIONS

The influence of the solid particle size, concentration and density as well as the effect of the carrier liquid on the break-up of a hollow cone suspension sheet was studied experimentally. The photographs of the sheet break-up have shown that the solid particles have an influence on the sheet break-up and its parameters. The increase of the solid particle concentration leads at first to increase the break-up length, a further increasing of the concentration leads to decrease the break-up length. The effect of the concentration seems to be influenced by the carrier liquid. The solid particle size and density affect the perforation mechanism in the dilute suspensions. In this case solid particles with high relaxation time (large diameter or high density) can not follow the turbulent fluctuations in the liquid sheet that leads to enlarge the velocity difference between the particles and the liquid. Accordingly, the perforation mechanism is promoted by the solid particles. The experimental results presented in this study find a good agreement with the theoretical study presented in [9] and also the results of break-up of abrasive water suspension jets presented in [11].

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