EXPERIMENTAL INVESTIGATION ON SURFACE WAVES AT THE EXIT OF HOLLOWCONE NOZZLES

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ABSTRACT

Measurement of the surface wave formation and propagation at Hollow Cone Nozzles (HCN) represents a complex challenge. Literature, dealing with this topic is rare. Analysis of the oscillations at the air core and the sheet seems to be inevitable to elucidate the link between disintegration of liquid sheets and drops formed. Based on the characterisation of the disintegration process resp. the lamella break-up an evaluation of nozzle efficiencies and the expected droplet size, should be possible. The present work describes a new technique for determination of the surface wave oscillations of at the exit of hollow cone nozzles. The identification of the surface waves is performed by a new sensor array, developed at the chair for Mechanical Process Engineering in Dortmund. Experiments are done to receive information about the amplitude, frequency and growth rates of the waves observed. For the validation of the results pictures were taken with a High Speed Camera.
Complementary to the frequency analysis the break-up length of thin conical liquid sheets is investigated by a measuring technique based on the conductivity of the atomized liquid.

1. INTRODUCTION

Various new publications are dealing with the disintegration of liquid sheets, but experimental work on the flow inside and outside of the nozzle is rather rare. However, in order to model the drop formation process, it is necessary to postulate a mechanism of sheet break-up and support a mathematical formulation of this mechanism. Break-up of attenuating lamella is most often attributed to aerodynamic waves, linked to exponential growth of amplitudes along streamlines. It can be seen from theory that at relatively low Weber numbers, instability due to long waves is dominant. In a new analysis reported by Senecal [1] it is shown that by increasing the Weber number a change from a long to a short wave regime is expected, with a growth rate independent on the sheet thickness. The onset of this regime can be more closely described for non viscous liquids as in Walzel [2] and Walzel, P. Broll, P. [3] by nondimensional parameters as

$$We^2 \cdot \kappa \cdot \rho^{*5/2} \geq 18{,}2 \tag{1}$$

with $We = \frac{v^2 d\rho}{\sigma}$, $\kappa = \frac{4\delta x}{\pi d^2}$ and $\rho^* = \frac{\rho_G}{\rho_L}$.

Other publications suggest the generation of centrifugal waves within the spin chamber to be the major cause for wave initiation and break up [4].

1.1 Breakup Length

The linear dispersion equation allows for determination of the maximum growthrate of waves corresponding to a certain wave length. It is assumed that droplets are formed from the sheet fragments originated from these waves after contracting to ligaments and finally disintegrating by the Rayleigh mechanism. This model requires a break up criterion for the sheets. An emperical parameter for the break up amplitude ratio usually is introduced and set to $\ln(A_Z/A_0) = 12$.

For long waves the break up length then is

$$L_Z / d = 8\kappa^{1/3} We^{-1/3} \rho^{*-2/3} \tag{2}$$

For short waves the break up length can be well estimated

$$L_Z / d = 18\sqrt{3}We^{-1}\rho^{*-3/2} \quad (3)$$

2. EXPERIMENTAL SETUP

2.1 Determination of the Break up length

With increasing distance from the nozzle exit conical sheets expand radially, giving rise to a periodic decrease of the sheet thickness along the streamlines. Considering the dependency of the produced droplet size on the sheet thickness at break up, it is important to understand the effects of both internal nozzle design and operating conditions on the break up length. Here, an experimental procedure based on the conductivity of the liquid is proposed to measure the break up length. This experimental technique has already been applied by several authors e.g. [5,6] in the past, generally in the case of diesel sprays.

The experimental set-up which is used for this study is presented in figure 1. The liquid to be atomized is kept in an open reservoir and pumped with a rotary pump to the nozzle. Six water/glycerol mixtures were investigated, varying in the dynamic viscosity from $1 < \eta_L < 80$ mPa s. The liquid pressure was graduated in steps between 0,5 and 1,6 bar, so that it was possible to cover a total range of $\mathrm{Re}_P = d\sqrt{\Delta p \rho}/\eta$ from 1000 up to 190000. An electrical sensor device, consisting of a power supply, a resistance and a digital data logging, is able to find the lamella break up position by means of the electrical conducting property of the liquid sheet. Two probes are operated simultaneously. One of them is placed inside the liquid sheet and the second acts as reference probe located at the same distance from the nozzle exit, but outside the sheet.

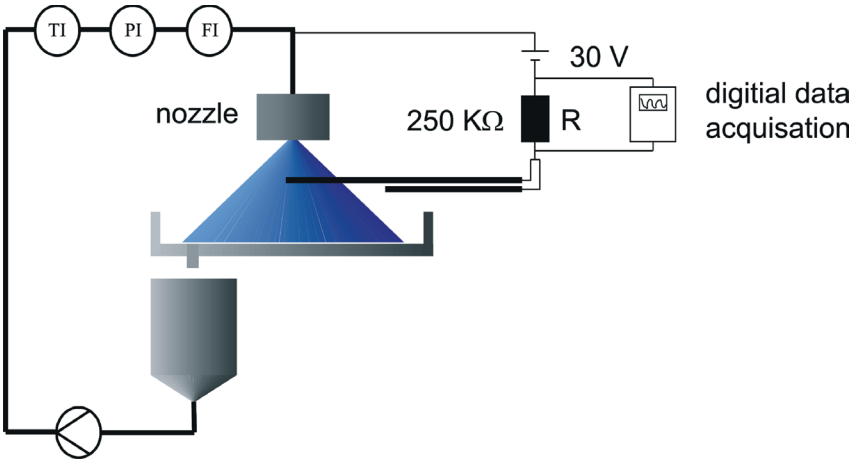

Figure1: Experimental set-up for the determination of the break up length

The technique allows for determination of a closed or open current circuit exploiting the conducting properties of the sheet. The spatial evolution of the voltage drop at the resistance *R* is visualized on a computer (fig. 2).

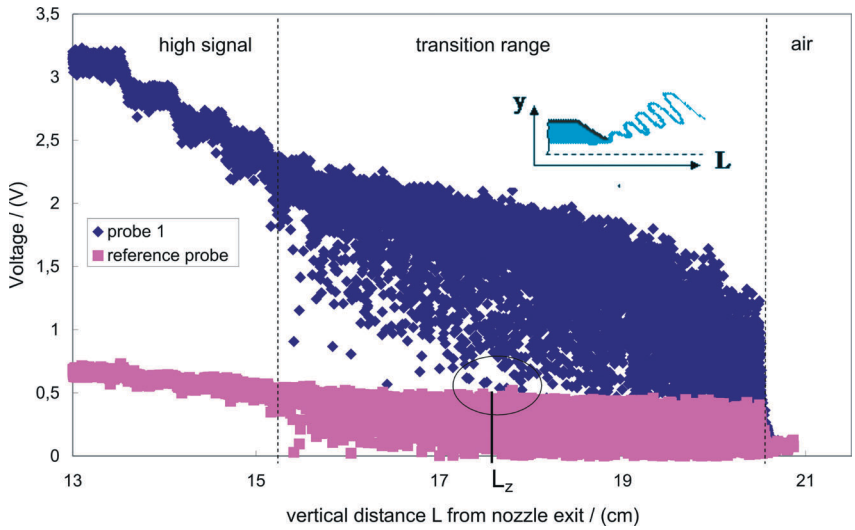

Figure 2: Evolution of the voltage drop as function of the vertical distance L from the nozzle exit

At the beginning of the measurement, the first probe is positioned near the nozzle exit, corresponding to a high voltage signal. By moving the probes downward the sheet, the ohmic resistance *R* of the fluid increases. At the point of break up the probe within the sheet gives identical low voltage signals as the reference probe. Since the break up point is not located at a fixed distance from the nozzle exit, the transition from the high to the low signal is not sharp. Regarding this observation the position of the lamella break up is considered to be at the position of the probe, when the lowest values of the lamella signal just starts to reach the values of the reference signal. This criterion tends to minimize the break up lengths to the first 10% of the widely distributed liquid break up length, but has the advantage of being reproducible. This measured break up length is the maximum distance for the location of the optical sensor array.

Figure 3 presents the evolution of dimensionless break up length L_z/d vs the Weber number at two given geometries (d = 8 mm, $\alpha = 60°$, $l/d = 0$ and $l/d = 1$). Both characteristics show a slight decrease for decreasing Ohnesorge numbers $On = \eta/(\sigma\rho d)^{1/2}$ and approach at higher Weber numbers. Increasing the Weber number or Reynolds number resp. leads to a more disturbed flow at the exit of the nozzle. Considering an increased "excitation" of the wavy oscillations, break up of the sheet takes place closer to the nozzle. Since the measured values show strong variation over the Weber number range, an interpretation of the results and a comparison with the theory is not yet possible. Further investigations will be done to receive an improved overview over the complete Ohnesorge and pressure range. The higher break up length for $l/d = 1$ can be explained by the slight decrease of the lamella velocity v and the increasing sheet thickness δ_0 at higher l/d-ratios. These effects prevail the decrease of the spray cone angle θ and lead to an increased break up length.

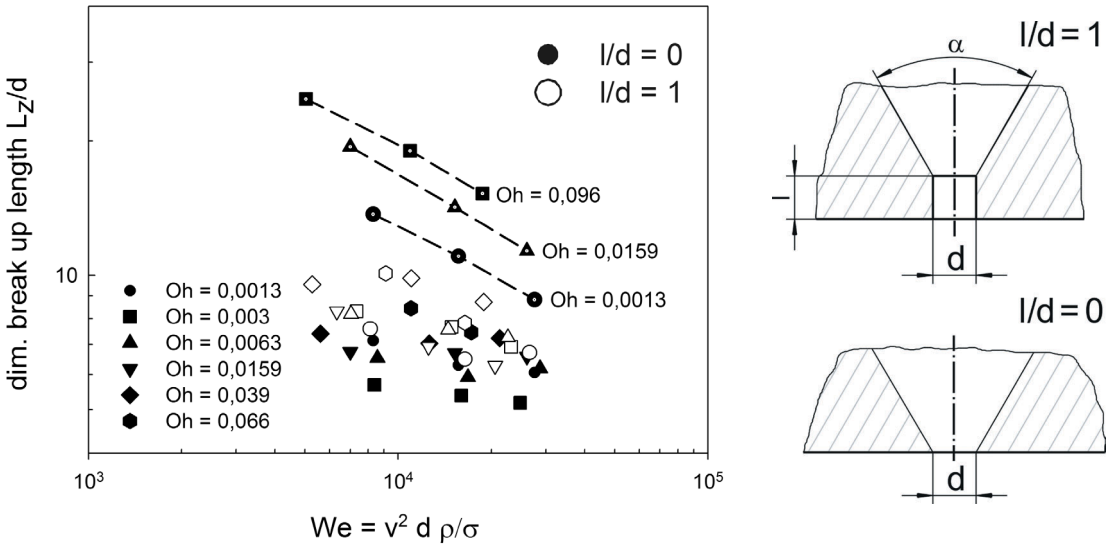

Figure 3: Break up length for a d = 8mm nozzle (l/d =1 und l/d = 0). Dotted lines calculated with eq. 2, based on velocity, sheet thickness and spray angle measurements.

2.2 Determination of the Surface Waves

Determination of surface waves at different process conditions is a highly demanding task for the measuring technique, as for reasonable analysis a high resolution in time and space is required. Moreover, the most common techniques, like ultrasonic, tomography, LDA und LPDA, are limited in the maximum fluid load or spray density. To avoid this problems, we are using a new sensor array, which was developed at our chair for Mechanical Process Engineering [8]. The sensor consists of glass or plastic (PMMA) fibres arranged in a comb matrix, which is directly placed inside a multiphase flow. Adopting the *Fresnel* effect we are able to measure the refractive index of the fluid in contact with the surface of the sensor tip. Hence, the sensor works as a transmitter and receiver at the same time (see fig. 4). Simultaneous and homogeneous incoupleing of a laser beam into the PMMA fibres is performed by a bending coupler operating as a beam splitter [9].

The running conditions and parts of the experimental set-up are identical to the one previously described (fig.4). The light source is a laser diode with a wavelength of 660 nm and a power rating of 50 mW. According to our process conditions a sensor array consisting of 45 single fibres was built with a fibre to fibre distance of 0,5 mm and an equal fibre diameter. The sensor comb is positioned perpendicular to the sheet in flow direction. The motion of the wavy sheet impinging on the sensor can be detected as a change of the local refractive index with a resolution of 0,5 mm in place and 0,1 ms in time. These oscillating changes are recorded by a line camera located at the remote tip of the fibres and indicate the distribution of the surface waves in space and time at a given sensor position. The line camera used was a Dalsa CL-P1, with a sensor length of 4096 pixel. Experiments were carried out for several nozzle geometries and different flow conditions [7].

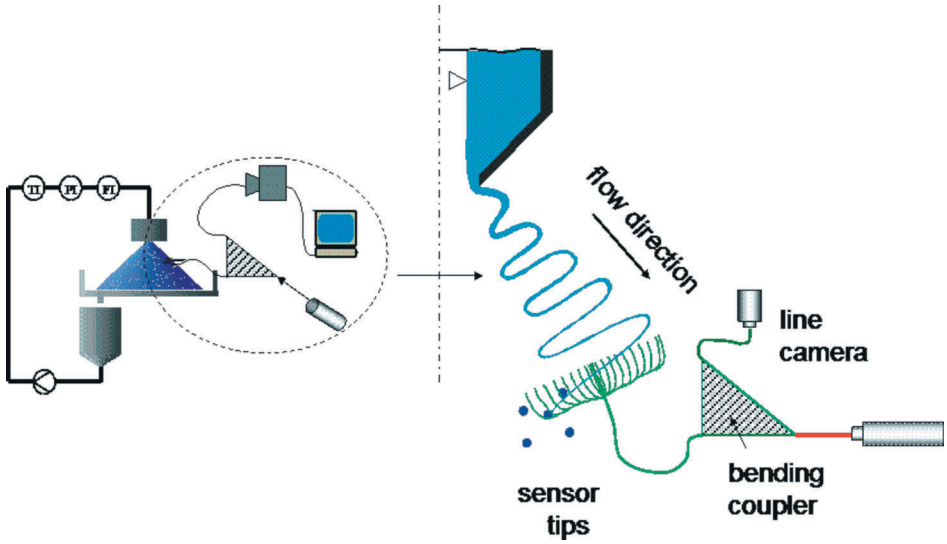

Figure 4: Experimental set-up for the determination of the surface waves

Primarily the sensor array was developed for the investigation of multiphase sprays at high loads. The ability of the sensor device in characterising and reading of waves on sheets was tested in a separate trial. A fan jet nozzle was mounted onto a shaker board allowing for well defined oscillations of the sheet emerging from the nozzle. Experiments were carried out for glycerine/water-mixtures with the highest and lowest refractive index. Different oscillation frequencies were investigated (10 Hz, 20 Hz, 50 Hz) and the sensor mounted within the sheet flow. The evaluation of the signals recorded has shown that the adjusted frequencies can be received by the help of a FFT or a wavelet analysis with a measuring error less than 5 %.

2.3 Evaluation and Results

Before the raw pictures of the sensor array can be applied to the frequency analysis, they have to undergo several, different treatment steps to receive a very high signal to noise-ratio. The evaluated pictures were analyzed by using a Fast Fourier Transformation and a Wavelet analysis. Another important issue is the separation and the pre-processing of the pure wave signal from the background noise. For this reason we are dealing with the development of a new algorithm for the picture evaluation.

Figure 5 shows a characteristic wavelet spectrum. The frequency and the period are plotted vs the time.

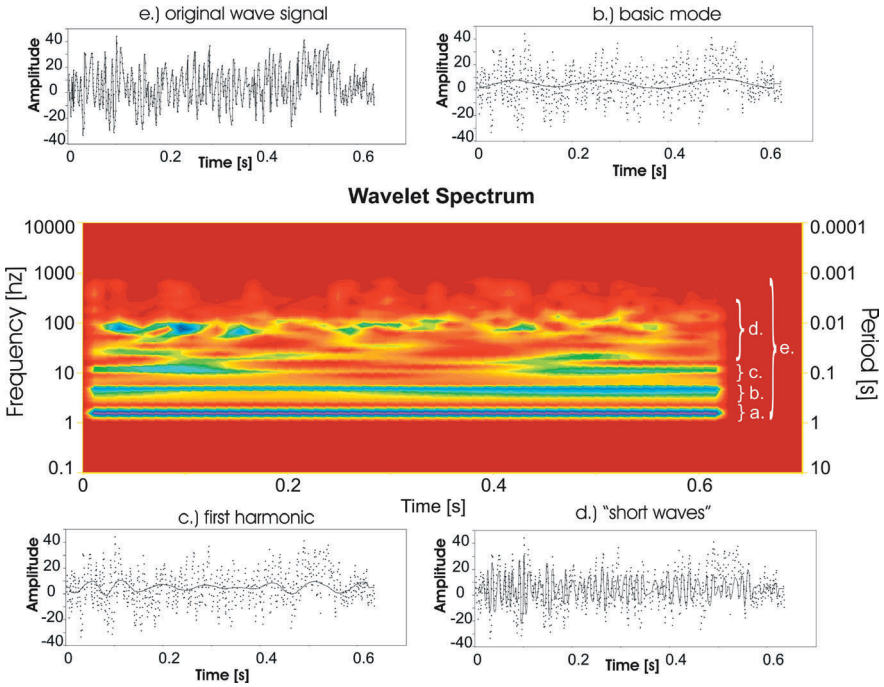

Fig. 5: Wavelet spectrum for an evaluated picture (pressure: 0,8 bar, viscosity: 80 mPa s); single wave bands as superposition to the original wave signal: a.) frame rate of the line camera b.) basic mode c.) first harmonic d.) "turbulence" e.) original wave signal

Compared to the Fast-Fourier-Transformation, this representation is dealing with wave bands in order to track the development of the frequencies as a function of the time. The investigation of the raw wave signal has shown a superposition of different spectra. Following spectra can be distinguished: a.) frame rate of the line camera b.) basic mode c.) first harmonic d.) “short waves or turbulences”.

Figure 6 presents the results of the frequency analysis for higher viscosities (η_{Gly2} = 80mPa s) depending on the pressure. The basic mode, resp. the first and second harmonic of the line camera have been suppressed by a high-pass filter. A comparison between the characteristics for lower wave bands shows that for l/d = 1 the measured frequencies are higher. This could be attributed to the less disturbed flow at the exit of the nozzle for higher l/d- ratios, leading to a more homogeneous “excitation” of the surface waves. At sharp-edged nozzles (l/d = 0) the increased turbulence at the exit inhibits a controlled and regular growth of the surface waves, also characterised by the non-uniform distribution of the wave bands at higher frequencies. In figure 7 it can be seen that for both viscosities the lower wave bands are in the same magnitude and remain nearly unchanged. These bands are irrelevant for the disintegration process and emerge assumedly through pressure variations of the spay cone, induced by the inner nozzle flow. Wave bands with higher energy content are observable at higher frequencies and it may be concluded that they are responsible for the break up of the sheet. Investigation resp. verification, if the higher frequencies are more closely connected with the disintegration process is still ongoing. For the time being a comparison of the exp. results with the theoretical approach of the linear stability theory is not yet possible. At first, we have to finish our evaluation for the whole viscosity range and we have to identify, which frequencies resp. wave bands are responsible for the disintegration process.

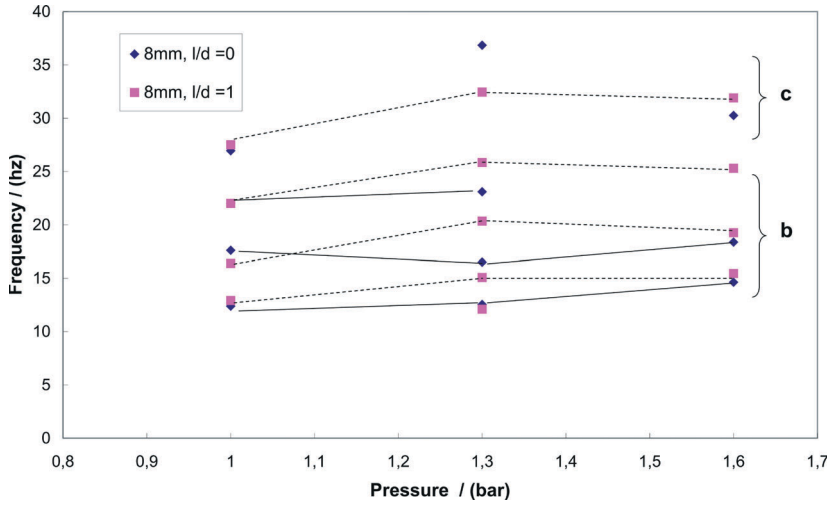

Figure 6: Frequency analysis for Glycerine 2 (η_{Gly2} =80 mPa s), 8mm, l/d = 0 und l/d = 1

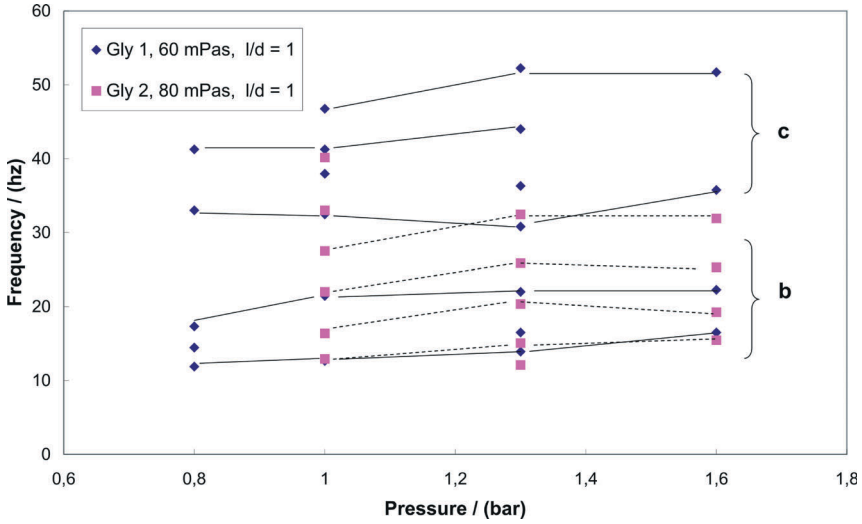

Figure 7: Comparison of frequency results for two different viscosities (η_{Gly1} = 60 mPa s, η_{Gly2} =80 mPa s),

Gratitude

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3. Nomenclature

d	nozzle diameter	[m]	λ	wave length	[m]
$k = 2\pi/\lambda$	wave number	[1/m]	ρ_L	liquid density	[kg/m^3]
l	length of orifice	[m]	ρ_G	gas density	[kg/m^3]
L	vertical distance from nozzle	[m]			
L_z	break up length	[m]	l	liquid	
R	ohmic resistance	[Ω]	g	gas	
$\dot{V}$	flow rate	[m^3/s]	z	break up	
v	sheet velocity	[m/s]			
x	running length	[m]			
			$Oh = \eta/(\sigma\rho d)^{1/2}$	Ohnesorge number	
			$Re_P = d(\Delta p/\rho)^{1/2}/\mu$	pressure Reynolds number	
σ	surface tension	[N/m]	$\varphi = v/u$	velocity coefficient	
μ_L	kinematic viscosity	[m^2/s]	$\Delta p^* = \Delta p d/\sigma$	Laplace Number	
θ	spray cone angle	[°]	$We = v^2 d\rho/\sigma$	Weber number	
ω	growth rates of amplitudes		$\kappa = C_D/\left[2\pi\varphi\sin(\theta/2)\right]$	sheet number	
δ	sheet thickness	[m]	$C_D = 4\dot{V}/\pi d^2 u$	discharge coefficient	
δ_0	sheet thickness at nozzle exit	[m]	$\delta^* = \rho_G/\rho$	density ratio	

4. References

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