EXPERIMENTAL STUDY OF THIN LIQUID FILM ULTRASONIC ATOMIZATION

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ABSTRACT

Ultrasonic atomization of liquids results from the unstable surface waves generated at the level of the thin liquid film that forms as the liquid spreads over the atomizing surface. This work continues our experimental analysis of both the thin liquid film disintegration phenomena and the ultrasonic atomizer sprays. The unstable surface waves, which are responsible for the droplets formation, are investigated using a high-speed camera technique at high magnification in order to get a good understanding of their effects on the droplets size. Laser techniques allow measurements of droplet parameters, Fraunhoffer diffraction for size distribution and Doppler effect for velocities. The effects of the working conditions on the spray characteristics are pointed out as well as those of the liquid properties.

1. INTRODUCTION

Ultrasonic disintegration of liquids into droplets results from the unstable surface waves generated at the free surface of a thin film that forms as the liquid spreads over the atomizing surface. This disintegration technique is mainly characterized by a fine atomization, a low spray velocity and a simple liquid feeding equipment. Ultrasonic atomizers are well suited for medical sprays, techniques such as humidification, combustion, and drying, applications in agriculture, metallic powders production and surface coating.

Some experimental investigations dealing with ultrasonic atomization are available in the literature: Lang (1962), Fogler and Timmerhaus (1965), Topp (1973), Chiba (1979), Bendig (1988),... The results presented show clearly that when the amplitude and the frequency of the acoustic field are tuned, unstable surface waves occur on the liquid free surface and give rise to droplets formation. The droplet diameter decreases by an increase of the working frequency. However, the lack of information on some operating conditions does not allow to have a good understanding of the effects of both the liquid properties (surface tension, viscosity) and the displacement amplitude of the atomizing surface.

To our knowledge, no author has ever measured the droplets velocity. Although all the authors agreed on the fact that surface waves do play a major role in the process of ultrasonic atomization, very little work has been done on the nature of the surface waves which generate the droplets.

Surface waves induced on the horizontal free surface of a liquid subject to vertical vibrations have been studied by Faraday (1831), Rayleigh (1894), Benjamin and Ursell (1954), Christiansen et al. (1992), Edwards and Fauve (1994),..., for working frequencies ranging from 2 to 550Hz.

Unexpected structures of the surface waves have been observed when the amplitude of the applied driving force exceeds a critical value. Parallel lines, squares, circles and hexagons can be observed both for rectangular and circular geometrical configuration of the liquid free surface as if the boundaries did not have any effect at all. In a recent study devoted to the analysis of the surface waves induced on the free surface of a thin liquid film for high working frequencies (ranging from 30 to 60 kHz), Sindayihebura and Bolle (1995 a) observed very regular square standing waves which did not exhibit strong sidewall effects. They did not detect surface waves patterns like spiral patterns, hexagons and quasi-patterns which occur when liquids are subjected to low frequency vibrations.

The present work provides an analysis of both the free liquid film behavior in the last step prior to the droplets formation and the spray characteristics. An experimental validation of the theoretical description of the thin liquid film ultrasonic disintegration is given. Measurements of the droplets velocity are presented for different working conditions. A link between the spray characteristics and those of the standing surface waves which give rise to the droplets formation is established. The effects of the liquid properties on the droplet diameters are also shown.

2. DROPLET FORMATION MECHANISM

When a liquid is delivered to the atomizing surface, a thin liquid film, the thickness of which varies from 80 to 300 μm according to the liquid flow rate (Cousin et al., 1997), forms as the liquid spreads out. Standing surface waves appear on its free surface when the amplitude of applied vibrating force exceeds a critical value. Very regular square standing surface waves, the amplitude of which grows with time, are detected in the beginning of the atomization process (Sindayihebura and Bolle, 1995 a). An example of these surface wave patterns is shown in Figure 1. Because of the high magnification, a free surface area of 0.67 mm^2 (0.92 x 0.73) is observed on each picture. The liquid film surface area is equal to 27.49 mm^2 .

This can explain the fact that a quasi-monodisperse spray could be obtained if parasite phenomena such as evaporation and coalescence do not occur. In general, the droplet diameter is assumed to be proportional to the wavelength of the surface waves. The decrease of the wavelength while the working frequency is increased is clearly shown on these photographs. Similar effects of the working frequency on the droplet diameter are observed as it will be seen in paragraph 3.2.

3. SPRAY CHARACTERISTICS

3.1 Experimental set-up

Both the droplet diameter and velocity distributions are examined. The volumetric droplet-distribution is measured using a Laser Malvern device based on Fraunhoffer diffraction.

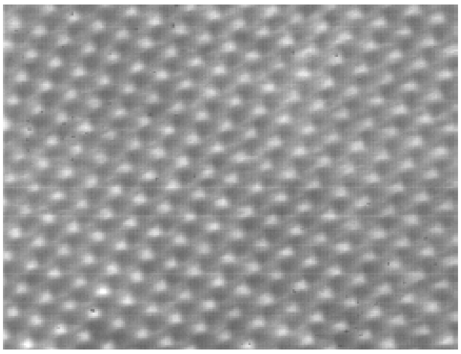
Our analysis uses the Sauter mean diameter (D_{32}) which can be defined as follows:

$$D_{32} = \frac{\sum p_i D_i^3}{\sum p_i D_i^2} \quad (1)$$

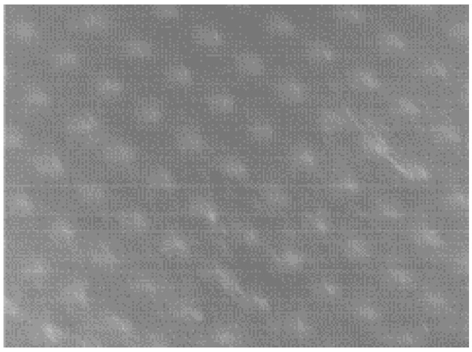
Axial and radial droplet-velocity distribution are studied by Laser Doppler anemometry. The effects of the working frequency on the droplets velocity are investigated using three different atomizers (33, 50 and 64 kHz), each ultrasonic atomizer working at its resonance frequency.

In order to analyze the influence of the liquid properties several mixtures of water-methanol and water-glycerol have been prepared. The properties of these liquids are presented in Table 1 (Handbook of Chemistry, 1976; mass fractions are considered). These liquids have been chosen in order to dissociate the surface tension effects from those of the viscosity as it can be seen in Figure 2.

For example, the effects of the surface tension can be analyzed using three experimental points (3, 6 and 9) when the liquid viscosity is fixed at 1.5*10^{-3} kg/ ms.



Working frequency : 50 kHz



Working frequency : 32 kHz

Figure 1. Standing surface waves patterns during the ultrasonic atomization.

	Mixture	Viscosity (10^{-3} kg/ms)	Surface tension (10^{-3} N/m)	Density (kg/m^3)
1	Water	1.00	72.75	1000
2	10% Methanol	1.33	59.04	981
3	16% Methanol	1.50	53.97	972
4	30% Methanol	1.79	43.02	951
5	47% Methanol	1.80	36.08	921
6	64% Methanol	1.50	31.84	885
7	72% Methanol	1.32	29.41	866
8	81% Methanol	1.10	27.04	843
9	15% Glycerol	1.49	72.67	1033
10	21% Glycerol	1.80	72.36	1048
11	36% Glycerol	3.09	71.54	1087

Table 1. Properties of tested liquids

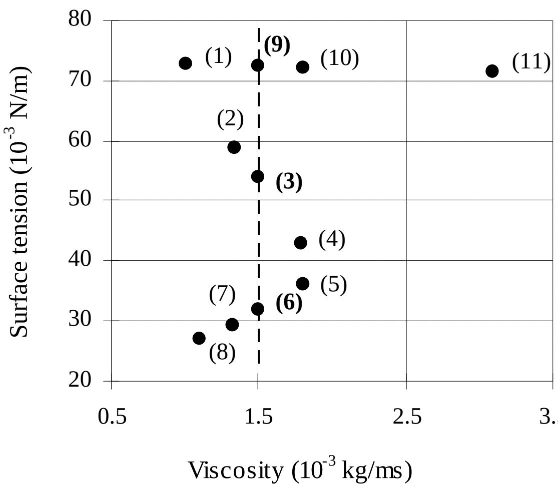


Figure 2. Experimental points.

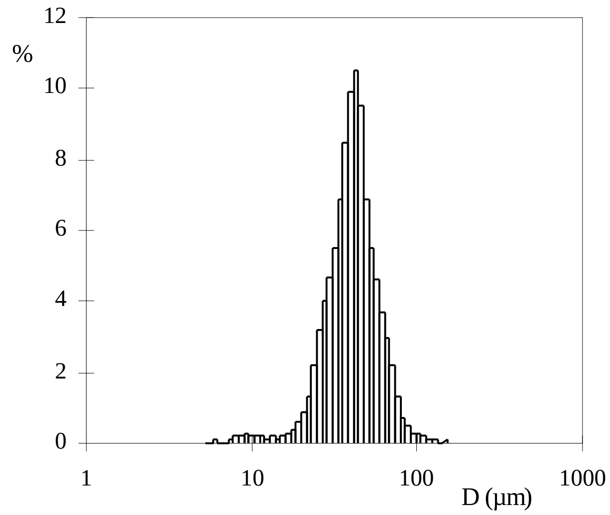


Figure 3. Volume droplet-size distribution (atomization of water at 50 kHz).

3.2 Droplets-size distribution

Ultrasonic sprays are characterized by a narrow, monodisperse distribution compared to those produced by classical atomizers. A typical droplet-size distribution is presented in Figure 3.

Effects of working frequency. The influence of the working frequency on the mean droplet diameter has been studied by several authors (Lang 1962, Crawford 1959, Drews 1979, Lacas et al. 1994, Sindayihebura 1995b). Figure 5 compares the results found in the literature. All the results appear to confirm that droplet mean diameter decreases with increasing of the working frequency.

Effects of the liquid flow rate. Figure 4 presents the Sauter mean diameter measurements versus the liquid flow rate. The experiments showed a slight increase of the droplet mean diameter with the growing liquid flow rate. In the surface wave theory the effects of the liquid flow rate are taken into account by means of the liquid film thickness. This latter is almost proportional to the liquid flow (Cousin et al. 1997). It has been pointed out that the liquid film thickness effects no longer exist when a critical value (about 0.06 mm) is reached(Sindayihebura 1995b). The observed liquid flow rate effects may be due to the ultrasonic cavitation phenomenon which occurs when the liquid film thickness grows.

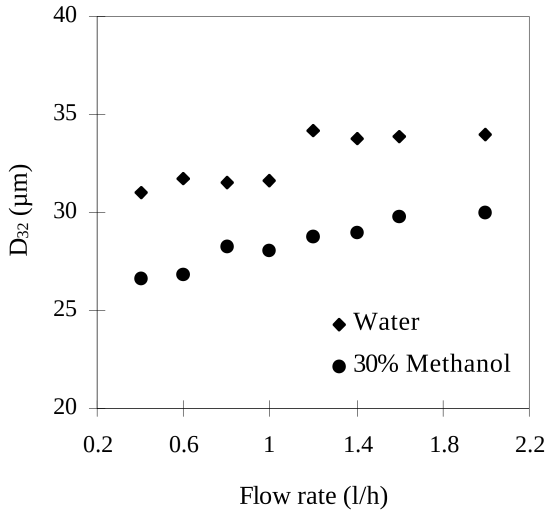


Figure 4. Influence of flow rate on droplet mean diameter.

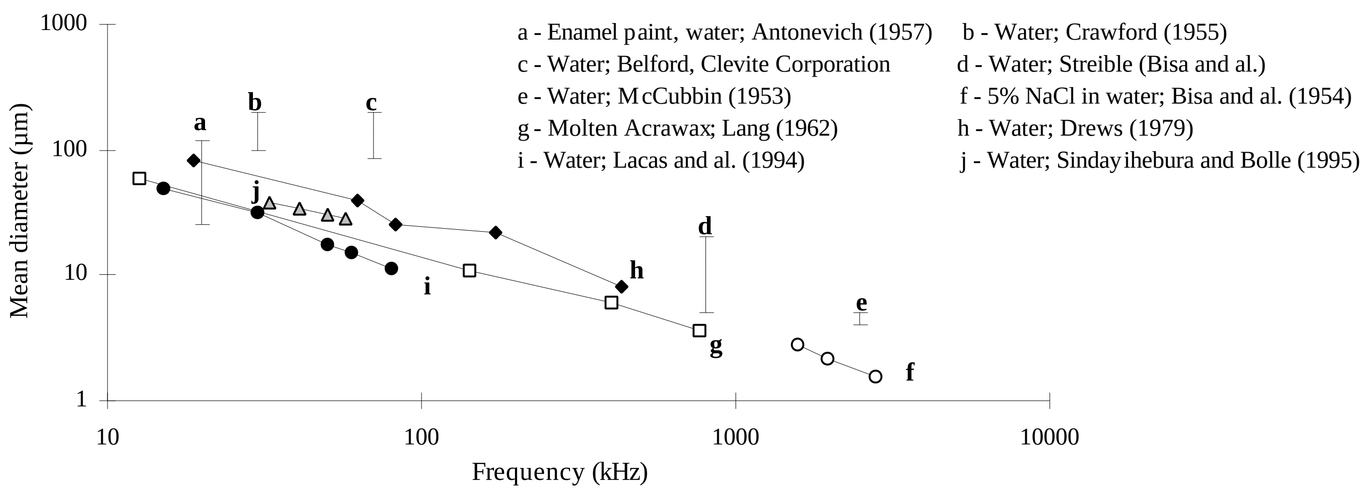


Figure 5. Droplet diameter data.

Effects of the liquid properties. Our experimental study involved viscosity and surface tension. The influence of each parameter is analyzed as well as the possible interaction between these effects.

Figure 6 shows plots for several values of the viscosity (a) and the surface tension (b). As the curves are almost parallel the two parameters seems to have independent effects on droplets mean diameter.

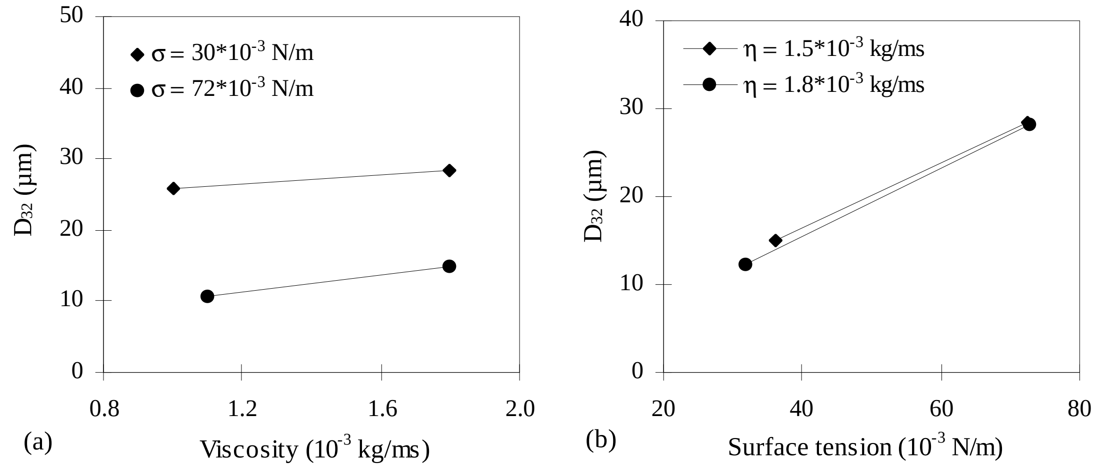


Figure 6. Interaction of effects (a. surface tension on viscosity; b. viscosity on surface tension).

Figure 7 shows the influence of the liquid viscosity on droplet mean diameter for a fixed flow rate (1.2 l/h). The surface tension of the four liquids used in this test was almost identical, $72 \pm 1\%$ (10^{-3} N/m^2).

For each flow rate and each frequency tested the plotting of the Sauter mean diameter versus surface tension follows the same curve. An example is shown in Figure 8 for a flow rate of 1.2 l/h, a frequency of 50 kHz and two values of viscosity.

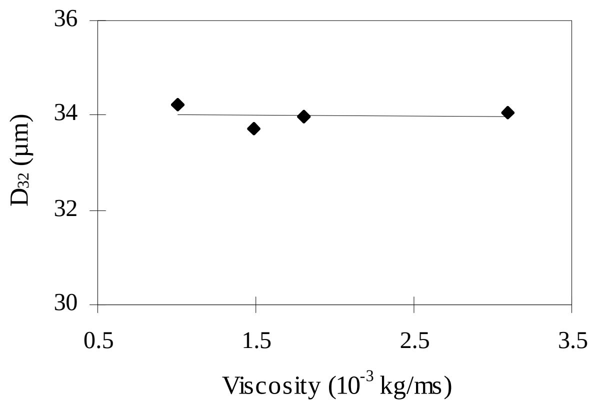


Figure 7. Influence of liquid viscosity on droplet mean diameter.

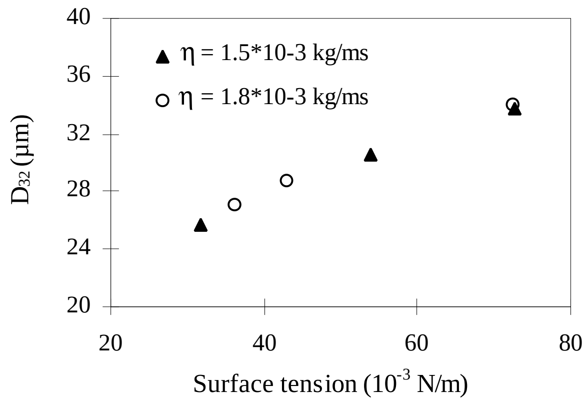


Figure 8. Influence of surface tension on droplet mean diameter.

The effect of the liquid viscosity on the droplet mean diameter is insignificant.

Another phenomenon has been observed during our experiments with viscous liquids. The liquid passing through the atomizer's feeding channel is heated up by the combined action of the vibrating energy losses and the viscous dissipation. When the liquid spreads over the atomizing surface its temperature in fact has increased. The temperature gradient grows as the liquid viscosity increases. This heating phenomenon may hide the effect of the liquid viscosity on the droplet size. Liquid heating inside the atomizer is a disturbing phenomenon for the experimental work but it can be useful for some applications. A highly viscous liquid could be sprayed as well as a lower one because of the internal decrease of the viscosity.

Droplet mean diameter increases as the surface tension grows.

3.3 Droplet velocity distribution

Figure 9 shows a typical velocity distribution. The measured radial velocity values are very small. It means that in ultrasonic atomization the droplets are ejected perpendicularly to the free liquid film surface. We can conclude that ultrasonic sprays are mainly characterized by the axial velocity.

In Figure 10 droplet mean axial velocities are plotted for several liquid flow rates and for three working frequencies. We can see that atomizers which work at higher frequencies produce droplets with a greater initial velocity.

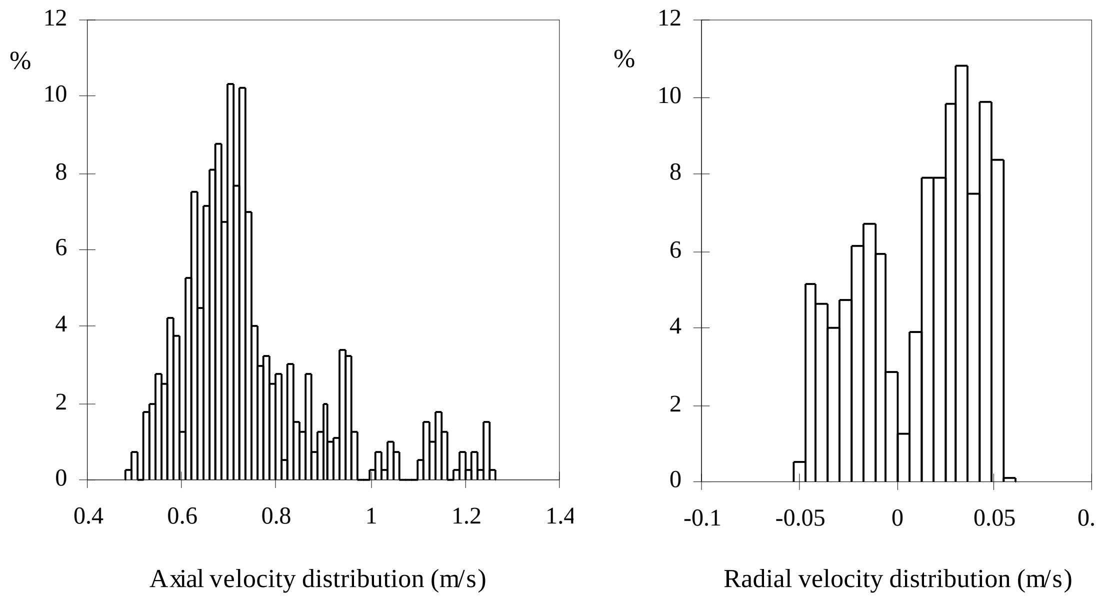


Figure 9. Droplets-velocity distribution .

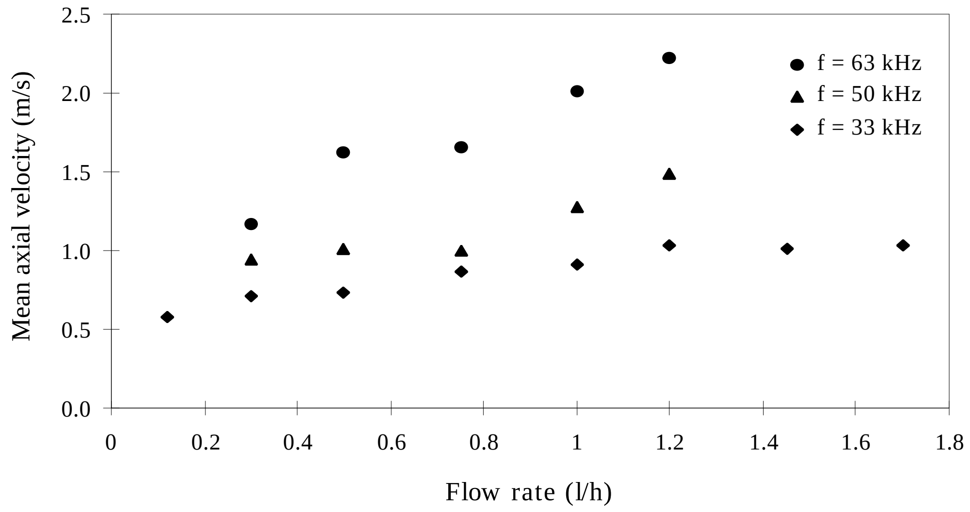


Figure 10. Influence of flow rate and working frequency on mean droplet velocity.

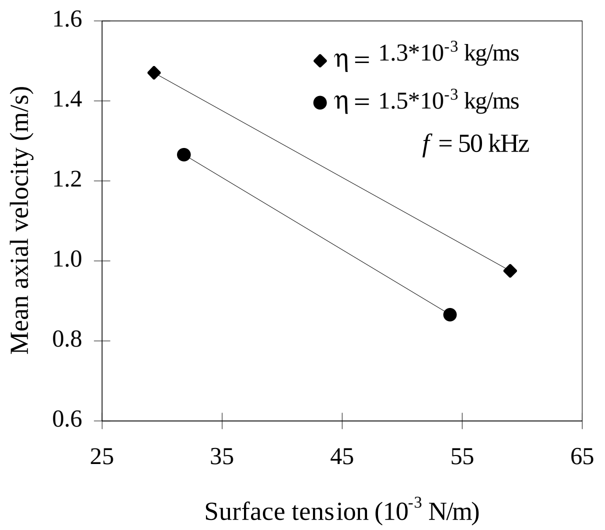


Figure 11. Influence of surface tension on droplet mean axial velocity.

Similar results are obtained by increasing the flow rate.

In order to examine the influence of the surface tension on droplets velocities experiments are made with several mixtures of water and methanol (Table 1, liquids 1-8). Figure 11 shows the measured mean velocities versus surface tension. These results show that the initial velocities decrease with the increase of the liquid surface tension.

4. DROPLET MEAN DIAMETER PREDICTION

Surface waves theory in ultrasonic atomization is based on the hypothesis that the droplets are emitted from the crests of the unstable surface waves (Drews 1979). As thousands of unstable surface waves can be generated on a vibrating free liquid film, it is assumed that the droplets are formed from the crests of the most rapidly growing unstable surface waves.

The resulting droplet mean diameter $\bar{d}$ is taken proportional to the wavelength. The mathematical modeling assumes a conical shape of surface waves as shown in Figure 12.

Assuming that the fraction of the liquid ejected from a crest forms a spherical droplet the following relationship can be written:

$$\bar{d} = k_0\ \lambda_s \qquad \text{where} \qquad k_0 = \frac{k}{2}\sqrt[3]{k_1} \qquad H = k_1\ \lambda_s$$

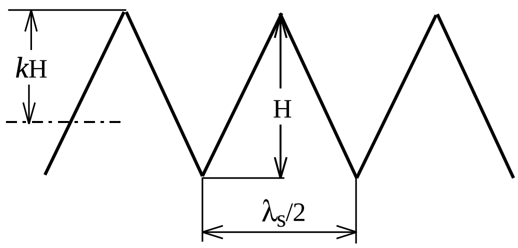


Figure 12. Modeling of surface waves.

The proportionality constant k_0 is determined experimentally. A formula for the prediction of the most rapidly growing surface wavelength λ_s, which takes into account all the main parameters, has been established in a stability analysis of the liquid free surface just before the ultrasonic atomization process (Sindayihebura 1995b). This analysis was based on the Navier-Stokes equations (Eq. 2).

$$\frac{2}{\pi\ f^2 \lambda_s}\left(4\,\frac{\sigma\pi^2}{\rho\lambda_s^2}+g\right)\tanh\left(\frac{2\pi\ h}{\lambda_s}\right)+0.2\left[\frac{\pi\ a_0}{\lambda_s}\tanh\left(\frac{2\pi\ h}{\lambda_s}\right)\right]^{½} - 1.04\ = \ 0 \qquad (2)$$

The values of k_0 were calculated using different working frequencies (different ultrasonic atomizers) - Cousin et al. 1997. It was pointed out that k_0 does not vary with the working frequency. As an example, for a water flow rate equal to $1.1\ 10^{-7}\ m^3\ /\ s$, the following averaged value was found for a series of measurements in the range of 32 up to 58 kHz:

$$k_0 = \frac{D_{32}}{\lambda_s} = 0.33$$

Mixture	Wavelength -calculated- λs (μm)	Mean diameter -measured- D_{32} (μm)	k_0
Water	91.32	31.02	0.34
10% Methanol	85.80	29.60	0.35
16% Methanol	83.57	28.34	0.34
30% Methanol	78.13	26.61	0.34
47% Methanol	74.51	24.56	0.33
64% Methanol	72.45	23.12	0.32
72% Methanol	71.10	24.65	0.35
81% Methanol	69.78	25.10	0.36
15% Glycerol	90.33	32.41	0.36
21%Glycerol	92.04	32.37	0.35
36% Glycerol	88.36	31.82	0.36

Table 2. Proportionality constant (k_0) values ($\dot{V} = 1.1\ 10^{-7}\ m^3\ /\ s$)

The values of D_{32} were obtained by measurements while those of λ_s were calculated from Eq.(2).

In this paper, the k_0 values were calculated using liquids of different properties.

Detailed results are presented in Table 2. According to these results, Eq.(2) can be used to predict the droplet mean diameter D_{32} substituting λ_s by:

$$\lambda_s = \frac{D_{32}}{0.34}$$

5. CONCLUSIONS

This paper presents a systematic experimental study of thin liquid film ultrasonic atomization. The structure of unstable surface waves which give rise to the droplets formation is observed and photographed. The relationship between the droplet mean diameter and the wavelength of the most rapidly growing unstable surface waves is determined using different liquids. Measurements of the droplet velocity are presented.

The liquid properties effects on both the droplet mean diameter and the droplet velocity are studied.

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NOMENCLATURE

a_0 - displacement amplitude of the atomizing surface;

$\bar{d}$ - droplet mean diameter;

D_{32} - Sauter droplet mean diameter;

D_i - droplet diameter range;

f - frequency of the ultrasonic vibration;

g - gravitational acceleration;

h - liquid film thickness;

H - height of surface waves crests;

p_i - probability for droplets to have the diameter into the range D_i;

$\dot{V}$ - liquid flow rate;

k_0 - proportionality constant;

l_s - surface wave wavelength;

h - liquid viscosity;

r - liquid density;

s - liquid surface tension.