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An experimental study of atomization of a liquid film subjected to an external forcing

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Abstract

Atomization of liquids in a spray is an important process in many industrial applications and particularly in the aero-engine field. The objective of this study is to validate a new concept of injectors which couples the shearing effects with the principle of ultrasonic atomization. The latter consists of using piezoelectric actuators to generate the oscillations of a wall in contact with the liquid film. This excitation (frequency: 1 to 50 kHz) perpendicular to the liquid film surface creates Faraday instabilities at the liquid/air interface. Amplitudes higher than a defined threshold value induce the break-up of ligaments and the formation of fine droplets. As result, Faraday's instabilities are generated at the interface leading to the production of droplets which size and acceleration threshold are dependant on the excitation parameters (oscillation frequency and amplitude) and liquid properties (density and surface tension). In this paper, laws deduced from theories or experiments for thick steady fluids are compared to experimental results obtained with a thin liquid film (300 µm and 1 mm) flowing on a wall and sheared by an external high speed air flow up to 100 m/s.

Introduction

Conventional air-blast injectors in today's aircraft engines use aerodynamic shearing effects to atomize the fuel. Two high speed co-flowing airstreams disturb the liquid sheet, leading to the development of interfacial instabilities. This high shear effect causes the disruption of the liquid film in a spray of fine droplets. The smaller the droplets, the better the mixing process between air and fuel. Thus the efficiency of the combustion and the level of pollutant emissions depend on the ability of the pulverization to produce very small droplets. However, in some conditions such as high-altitude re-ignition, air speed, pressure and temperature are too low to allow a good pulverization.

Ultrasonic atomization of liquids is currently used in a wide range of industrial and research applications. H.L. Berger [2] lists and describes a sampling of the more common applications of the ultrasonic technology. Earlier observations of a liquid film formed on a vibrating surface where obtained by Faraday in 1831 [3]. Since then, many studies have been conducted to understand this mechanism and to find links between the excitation parameters, the development of standing waves at the free surface and characteristics of resultant droplets. Ultrasonic atomization resides in submitting a thin liquid film to a normal oscillation with adjustable ultrasonic frequency and amplitude. The liquid absorbs some of the vibrational energy, generating waves at the free surface of the film. Waves form a stationary rectangular grid in the liquid film with regularly alternating crests and troughs. This phenomenon is called Faraday's instabilities. When the resonance frequency is reached, the amplitude of oscillations grows until droplets are created from the crest of a wave as symbolically depicted by Drews [5]. The main advantage of this atomization process is its ability to generate a spray with a narrow distribution. In addition, as we shall see below, a control of the drop size is available by way of the frequency while the acceleration controls independently the flux. An experimental study of the atomization process has been done for complementing the work of M. Lalo *and al* published in ICLASS 2006. It includes an analysis of the interfacial waves and the characterization of the actuator. Water, ethanol and soapsuds were used as the test liquids to clarify the effects of surface tension, density and viscosity on the ultrasonic atomization. In order to analyze the influence of liquid properties several solutions have been prepared [Table 2]. These liquids have been chosen in order to dissociate the surface tension and density effects from viscosity. Also, the effect of excitation frequency and amplitude of excitation on the ultrasonic were investigated

Faraday's instabilities

The first studies of stationary waves on the free surface of a liquid subjected to periodic vertical forcing were reported by Faraday (1831), he obtained experimentally a frequency of the surface waves equal to half the excitation frequency $f_m = f/2$.

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In. 1871, Kelvin derived the well known equation for the speed C_m of the waves

$$C_m = \sqrt{\tanh\left(\frac{2\pi}{\lambda_m} h\right)\cdot\left(\frac{k_m^3 \sigma}{\rho} + k_m g\right)}\;;\; k_m = \frac{2\pi}{\lambda_m} \tag{1}$$

On the basis of Faraday (1831), Kelvin (1871) and Rayleigh (1883) works on capillary waves and on sound theory, Lang (1962) deduced the relation for wavelength

$$\lambda_m = \left(\frac{8\,\pi\,\sigma}{\rho f^{\,2}}\right)^{1/3} \tag{2}$$

With accordingly to the following hypothesis:
H 1: $\lambda_m << h$
H 2: capillary forces >> gravity forces
H 3: $f_{\,m} = f/2$

From simplified linear instability analysis Benjamin and Ursell (1954) established the equation of the amplitude of the liquid surface. Recently, the prediction of the most rapidly growing surface wavelength, which takes into account all the main parameters, has been established by Sindayihebura [4] in a stability analysis of the liquid free surface just before the ultrasonic atomization processes.

$$\omega_m^2 = \frac{4k_m\left(\frac{\sigma}{\rho}k_m^2 + g\right)\tanh(k_m h)}{1.04 - 0.10\left(2\alpha_0 k_m \tanh(k_m h)\right)^{1/2}} \tag{3}$$

If the influence of gravity forces is negligible compared to capillary forces, the liquid film is thin and the displacement amplitude of excitation small as compared with the wavelength. Equation (3) reduced to equation (2).

Above some acceleration threshold (a_c), these waves form ligaments that break and produce droplets. Goodridge [8] proposed the following correlation:

$$a_c \approx 0.261\left(\frac{\sigma}{\rho}\right)^{1/3}\omega_0^{4/3} \tag{4}$$

Goodridge's equation (4) is based on experimental results obtained with a constant liquid layer thickness equal to 10cm. Baluteau [9] confirmed the values of the exponents on the dependent variables. Pyrtel [10] proposed another correlation where the effects of the liquid film thickness are taken into account

$$a_c \approx \beta f^{\,16/9} h^{-2/3}\left(\frac{\sigma}{\rho}\right)^{1/9}$$
$$\beta = 318.5\cdot 10^{-6}\,(m^{4/3}) \tag{5}$$

Above this acceleration threshold, Lang (1962) established an expression relating the wavelength to the droplet size through an empirical constant.

$$d_{30} = 0.34\left(\frac{8\pi\sigma}{\rho f^2}\right)^{1/3} \tag{6}$$

Experimental investigation conducted by Lacas *et al.* [7] or Sindayihebura [4] showed a decrease in the drop diameter when the working frequency increases. Those experimental observations confirm Lang's equations.

Experimental tools

The injector system is described in detail in Lalo *et al.* [1]. The experimental set-up allows experiments with air velocities from 0 to 100m/s and water velocities ranged between 0.4 and 2.32m/s. The ultrasonic device includes a piezoelectric actuator and a mechanical amplification system. Two kinds of mechanical systems were tested. One consists of a girder (length 100 cm, width 20 cm and thickness 3 cm) embedded on one side, the other corresponds to a sonotrode (gain of amplitudes of displacement equal 5). The atomization takes place at the free end of the mechanical system. A sinusoidal reference signal to the actuator is supplied by a frequency generator (Metrix MTX3240) and is amplified by a voltage amplifier (LA75C, CEDRAT, gain 20). The mechanical amplification system increases the excitation displacement. The girder or sonotrode is flush mounted with the prefilming area so that the liquid film coming from the tank undergoes an acceleration normal to its interface meanwhile vertical acceleration meanwhile it is perturbed by aerodynamic forces.

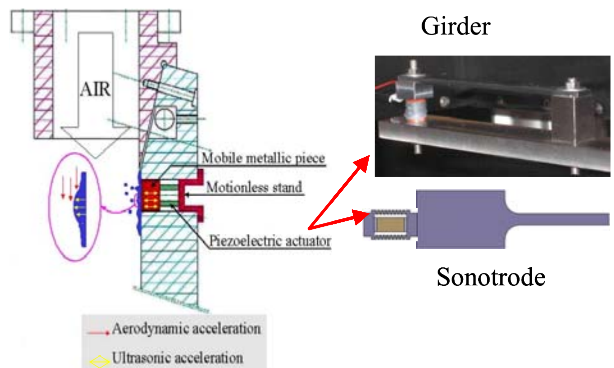

Figure 1. Image of the injection system after modifications for the active method

The effects of the working frequency on droplet size and threshold displacement are investigated using two different mechanisms of atomization, girder (1 kHz to 16 kHz) and three sonotrodes. (35 kHz, 45 kHz and 47 kHz).

Visualization. Front and side visualizations of the liquid film are carried out to qualitatively study the behavior of the liquid. Image acquisition is achieved by a CCD camera (768x576 Pixels), which is synchronized to a stroboscope at 25Hz.

Threshold displacement. The vibrating amplitude of the mechanical system is measured using a Polytec optical vibrometer, which detects surface of motion non-intrusively utilizing an interferometric technique. The helium-neon laser beam of the vibrometer is directed to the centre of the vibrating surface.

Drop size measurements. Experiments based on laser diffraction are conducted with a Malvern Spraytec system. The laser beam crosses the spray 5 mm above the atomizing device.

Results and Discussion

The following chapter presents the results and visualizations of the disintegration of a liquid film by ultrasonic atomization. At resonance frequency, which is a function of geometrical characteristics of the mechanical system, the direction of vibration is strictly perpendicular to the atomizing surface. When the amplitude of excitation is increased, the amplitude of the capillary waves increases correspondingly. Finally, tiny drops of liquid are ejected when the applied amplitude exceeds a critical value. As an example of the droplet atomization on the oscillating surface, photographs of the atomization phenomena of water are shown in figure 2. Images illustrate the case of a motionless liquid film placed on a horizontal plate. When the resonant frequency of the mechanical system is reached and the amplitude of excitation increases, the drop flattens and Faraday's instabilities appear on the interface (Figure 2 images 2-3). Once the displacement threshold is reached, break-up of ligaments and the formation of droplets start (Figure 2 image 3). When the amplitude of excitation is further increased, the ultrasonic atomization becomes more powerful and the initial liquid film is completely pulverized (figure 2 image 4). Experiments have also been conducted with droplets of the same liquid dropping on a vertical mechanical system submitted to ultrasonic oscillation. When hitting the active surface they are atomized into a spray of droplets.

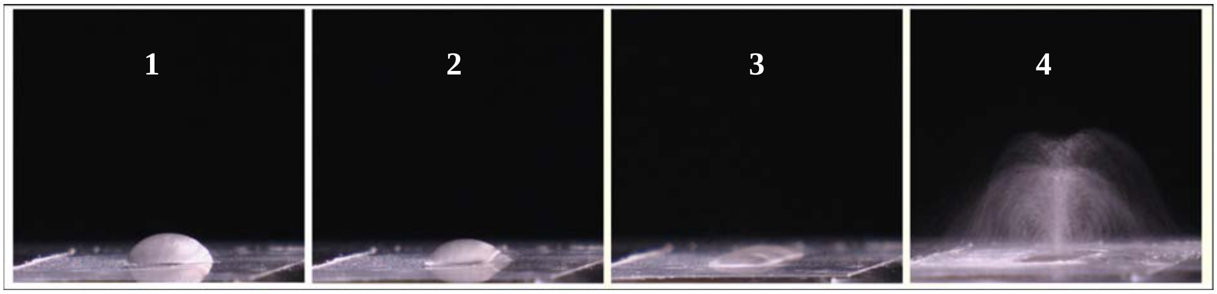

Figure 2. Visualization steps of the pulverization a liquid due to faraday instabilities – *f* = 35 kHz –

- **Displacement threshold measurements**

Key differences between the experimental investigations are presented in Table 1.

Table 1 : Summary of experimental conditions

	Frequency range	Film thickness
Goodridge (1997)	20 – 80 Hz	10 cm
Baluteau (2001)	25 – 150 Hz	1 cm
Pyrtel (2003	100 – 650 Hz	1 – 6 mm
Present work	1 – 45 kHz	< 1mm

Table 2 : properties of tested liquid

Solution	σ(N/m)	ρ(kg/m³)	ν(x10⁻⁶)(m²/s)
Ethanol	0.02412	785.04	1.368
Water +soapsuds	0.2843	997.048	0.89
Water	0.07653	997.048	0.89
Water+10% ethanol	0.04753	981.9	1.53

Figure 3 shows the dependency of the droplet ejection threshold on the excitation frequency. As the frequency increases the threshold decreases in a consistent manner as predicted by Goodridge and Baluteau [8, 9]. Pyrtel's results show a significant offset with the others authors. Since he explained this fact by the thinner film employed [10] – which would place us even higher in the diagram – this contradiction is the subject of an ongoing investigation.

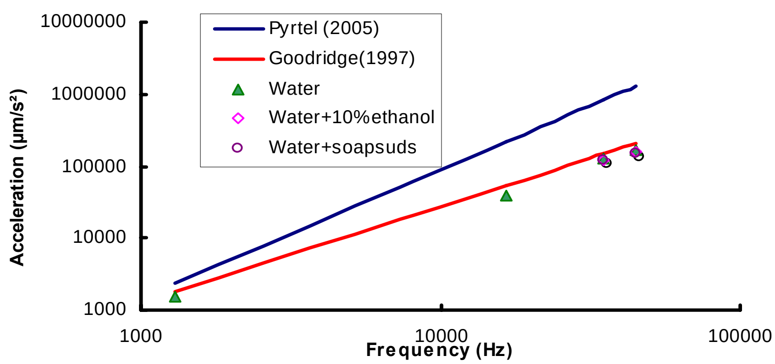

Figure 3. Threshold displacement as a function of the excitation frequency

- **Drop size distributions**

Ultrasonic sprays are characterized by a narrow, almost monodispersed distribution compared to those produced by classical atomizers. Surface-wave-theory in ultrasonic atomization is based on the hypothesis that the droplets are emitted from the crests of the unstable surface waves [5].

Influence of frequency. The effects of working frequency on the Sauter mean diameter (SMD) have been studied by several authors (Lang 1962, Sindayihebura 1997). Figure 4 compares different correlations found in literature to our experimental results. The experimental results confirm those found in literature. All the results confirm that the droplet mean diameter decreases when increasing the forcing frequency. The droplet mean diameter is approximately equal to 20µm when the excitation frequency is set to 50 kHz. Such sizes are favorable for an efficient combustion.

Influence of the liquid properties. Our experimental study involves viscosity, surface tension and density. The influence of each parameter is analyzed as well as the interaction between these effects.

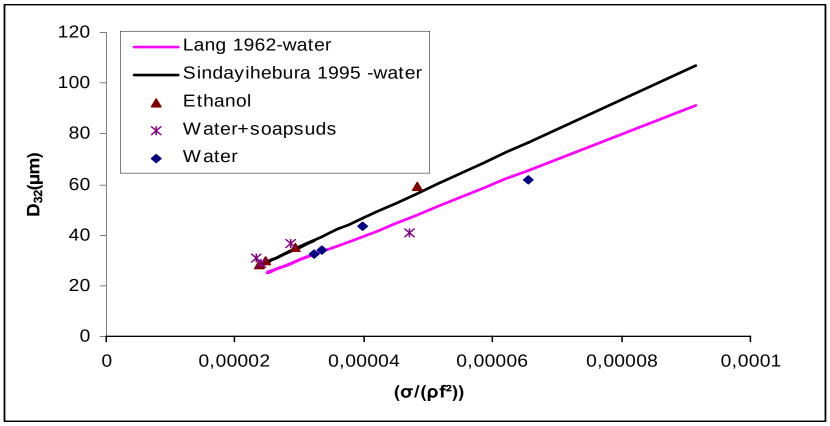

Figure 4. Effects of the liquid proprieties and the excitation frequency on the D_{32}

Figure 4 illustrates the variation of the SMD over the excitation frequency for multiple liquids. The linear dependency of D_{32} in $(\sigma/(\rho f^2))^{1/3}$ is well represented by Lang's equation (Eq.(6)) and confirmed by our experimental results.

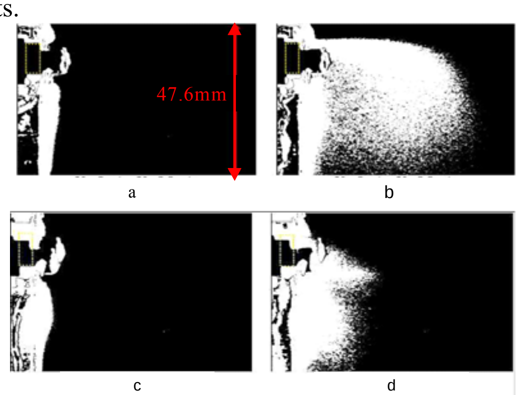

Figure 5. Illustrations of the combined effects of shearing instabilities– Faraday's instabilities on the spray penetration (cf Table 2: experimental conditions)

Table 3. Summary of experimental conditions

Image	Vg(m/s)	*f*(kHz)	U(mV)
a	0	0	0
b	0	14.7	90
c	10	0	0
d	10	14.3	90

Figure 5: image (a) shows the envelope of the film without airflow and excitation but with a liquid flow rate (V_l=0.9m/s). When the acceleration increases above the atomization threshold, the spray penetration is enhanced (Image b). Images (c) and (d) were taken with a 10m/s air crossflow (upstream to downstream). Again, when the actuator is on, a spray is produced that still penetrates the strong gas flow. The depth of penetration is somewhat lower compared with the zero gas velocity case because of the entrainment of the small droplets by the gas stream. These results validate the feasibility of the proposed active method on the prefilming area of an air assisted injector.

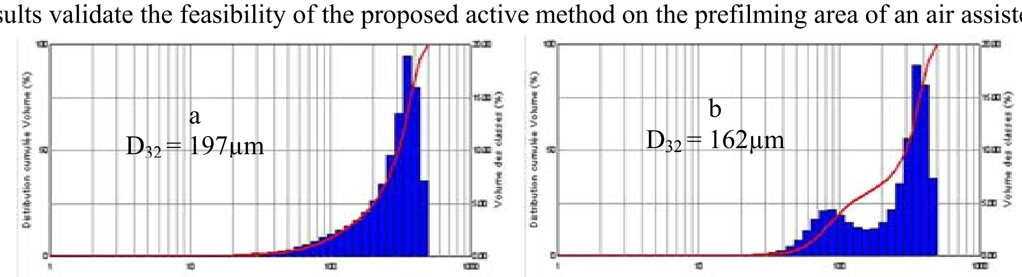

Figure 6. Effect of the active methods on the volume droplet – size distribution -V_g = 60m/s - h_l = 300µm - V_l = 0.9m/s (a) without excitation - (b) with excitation - f =15.4kHz - U = 140mV

Figure 6, image (a) shows the droplet size distribution from the liquid film atomization by shearing instabilities, at the atomization begins. As the excitation is added (Image b), the droplet size distribution changes and the D_{32} is reduced by 20 %. Image (b) shows two mechanisms of atomization can coexist influencing the size distribution.

Conclusion

The aim of this study was to investigate the assisted atomization of a liquid film and the consequences of an active method applied to the liquid phase. The drop size due to Faraday instabilities was found to obey Lang's law over the whole range of conditions considered, indicating that the forcing frequency controls the drop size. The acceleration threshold at the onset of atomisation has been determined and was found consistent with previous studies. Such a result is a good indication that the drop flux can be monitored by way of the acceleration, the later being independently controlled (by way of the actuator displacement). Finally, the actuator was proved efficient both on moving liquid films and in presence of a strong co-flowing gas stream. Thus, the technique is potentially suitable to control the drop size and the flux in air assisted injection devices. Progress are however necessary to quantify the flux of droplets as a function of the control parameters and aerodynamic conditions. Another step would be to extend the investigation to an axisymmetric geometry.

Acknowledgments

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Nomenclature

a_c threshold acceleration
f frequency
V velocity
ρ density
σ surface tension
D_{32} Sauter mean diameter
h film thickness
λ wavelength
α_0 displacement amplitude
k wave number
U voltage
g acceleration duet o gravity
C Velocity of the sound in liquid

Subscripts
g gas
l liquid
m surface wave

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