Influence of Signal Properties on ElectroHydroDynamic Primary Break-up of Thin Sheets of Dielectric Liquid

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Abstract

For more than three years now, a new electrohydrodynamic (EHD) actuator based on a dielectric barrier injection system has been developed in order to enhance fuel atomization in air blast atomizers. Dielectric barrier injection devices are very interesting because they allow reaching very high electric field while preventing the occurrence of electric sparks. Experiments have been carried out on thin sheets of commercial Diesel oil without active surface agent. The flow rate and the liquid sheet thickness are similar to the ones used in turbo engines. In the contrary of typical air blast atomizers, the atomization is not obtained by the use of a shear air flow or any other form of mechanical disturbance but only with the help of electric forces. As a consequence, the liquid sheet produced by the injector is stable when the EHD actuator is switched off. On the other hand, it could be fully atomized when the actuator is on. Investigations have been made with a high speed camera on the primary break-up modes and on the droplet formation mechanisms. The present study mainly focuses on the influence of the signal shape, amplitude, and frequency.

Introduction

Air blast atomizers are commonly used in aeronautical engines. In these atomizers, the fuel is injected at low pressure through an annular slot. A tubular sheet of carburant is therefore produced at the outer edge. The disintegration of the thin tubular sheet is obtained by the use of two co-flowing airstreams which peel the surface of the liquid. Unfortunately, a high air velocity is needed in order to obtain a fine atomization. This is the main drawback of air blast atomizers. With a too slow air velocity, the atomization is weak and the fuel combustion becomes ineffective. Moreover, when the air velocity is below a limit of few meters per second, the sheet of fuel is not sprayed anymore. This condition could be encountered in the problem of engine relight during a flight at high altitudes, where the pressure and the temperature are very low.

In order to limit this drawback two approaches are developed. The first one is based on passive methods. In this approach, the work focuses on physical understanding of break-up mechanisms in order to optimize both geometrical parameters and fuel properties [1] ,[2] ,[3] ,[4] .

The second one is focused on active methods. The aim is to induce or excite the sheet instabilities by using actuators. Some actuators as plasma actuators are used to act on the air streams [5] . Others as piezo-electric [6] or electric actuators act directly on the liquid sheet.

In the present work, the sheet of fuel is directly destabilized and disintegrated by an electrohydrodynamic (EHD) actuator.

A lot of studies have been carried out on fuel electrospraying. The first experiments and modeling have been made on simple pressure atomizers [7] . These studies have been completed and fully modeled by Shrimpton [7] . It has been demonstrated that in such a device, the size of the droplets is correlated to the injected charge density. Unfortunately, the maximum injected charge density and then the size of droplet diameter is limited by a corona discharge surrounding the liquid jet as it flows out from the atomizer. Some studies have been also made on pressure swirl atomizers. The electric forces are superimposing with the mechanical ones in order to improve the atomization.

In industrial atomizers, the fuel is injected through an annular slit. Such devices produce thin tubular sheets of fuel. This shape is very efficient for atomization but difficult to investigate. More than a decade of studies in atomization processes has proved that the mechanisms of disintegration are similar on cylindrical and plane thin sheets of liquid. In this article, all the experiments have been performed on a plane sheet.

In this study a new method is proposed to obtain the fuel atomization of the liquid sheet in air blast atomizers even if the air velocity is equal to zero. Atomization is only due to electric forces produced by an EHD actuator. As there are no co-flowing airstreams and as the fuel is injected at low pressure, the liquid sheet is stable when the EHD actuator is turned off.

When an AC signal is applied on the actuator, the sheet of fuel is shacked by electric forces. Three disintegration modes depending on liquid velocity and on signal amplitude are analyzed and described. In the flapping mode, the sheet waves as a function of both the liquid velocity and the signal frequency. The sheet wave amplitude can reach more than a 1cm. At relatively high liquid velocity, the sheet is greatly affected by charge injection. High frequency disturbances in the sheet become more predominant until perpendicular ligaments and then holes appear, giving rise to a perforated sheet. In the disintegration mode, the sheet is fully atomized. The higher the frequency is, more numerous are the droplets, and smaller is the droplets size. A comparison between air blast and EHD atomization is made in order to underline similarities and differences of the two processes. It was demonstrated that the primary atomization obtained with a 2 kHz signal frequency is equivalent to the one observed with a 25 m.s^{-1} co-flowing air stream, which is an important advance in EHD technology. Investigations on the primary break-up characteristics have been made with a high speed camera on the primary break-up and on the droplet formation mechanism.

Air blast Atomization

In industrial air blast atomizers, the fuel is injected at low pressure through an annular slot. This produces a tubular sheet of fuel which is disintegrated into droplets by two co-flowing airstreams. Unfortunately, a high air velocity is needed in order to obtain a fine atomization. This is the main drawback of air blast atomizers.

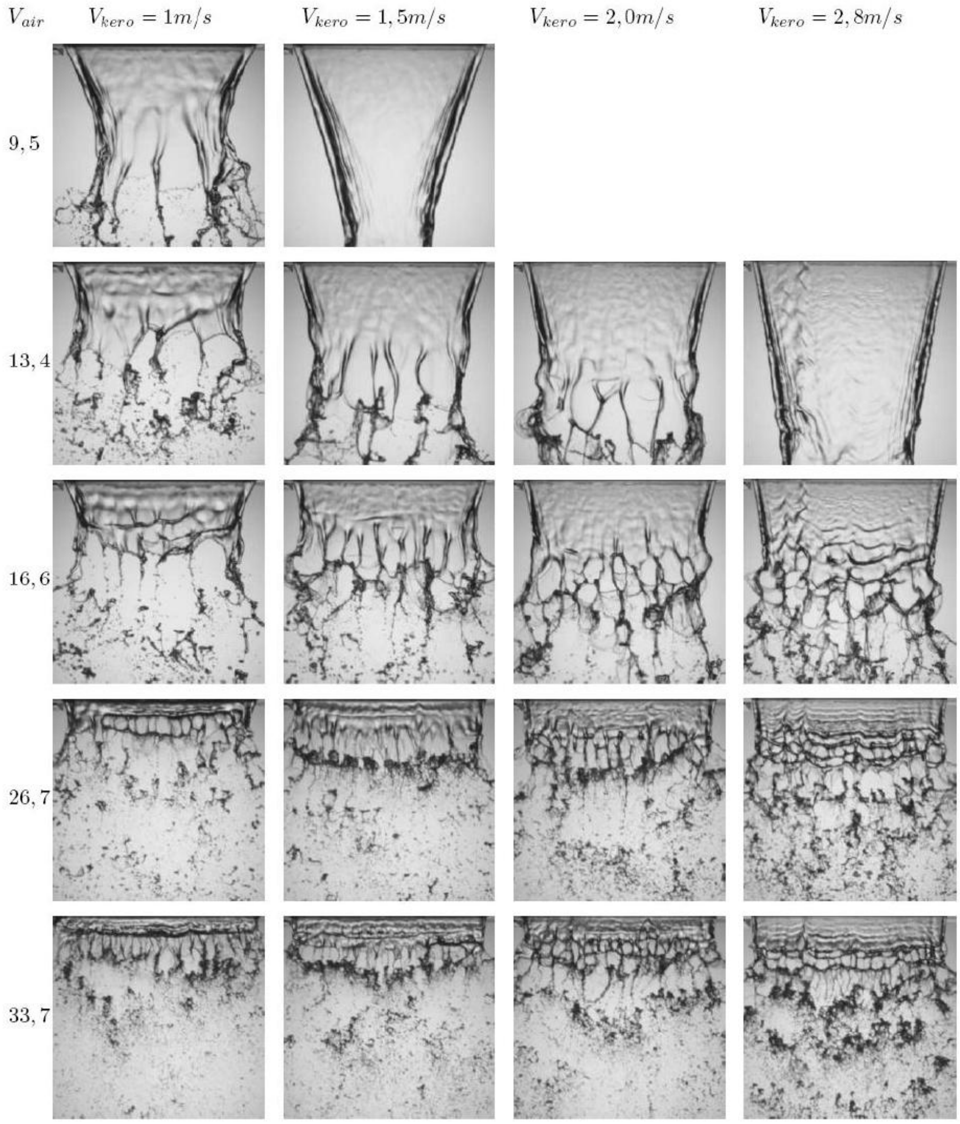


Figure 1 Shadow images of an air-blast atomization of plane sheets of kerosene for various air and gas velocities [12]

A very interesting study on air-blast atomization has been made by Larricq-Fourcade [12]. He demonstrated that with an air velocity below 30 $m.s^{-1}$ the atomization is too weak for fuel ignition. This problem could be encountered in relight ignition at high altitude, where the pressure and the temperature are very low. When the air velocity is less than 10 $m.s^{-1}$ the sheet of fuel is not sprayed anymore. Figure 1 is an example of the results obtained by Larricq-Fourcade with a sheet of kerosene of 300 µm thickness.

It can be observed that the relative velocity between liquid and gas is not a good parameter to predict the good atomization of the sheet and the reader is invited to consult [12] in order to haveadditioinal information.

Experimental setup

In this article, experiments have been carried out on a plane sheet of carburant. A schematic of the experimental setup is presented in Figure 2. The fuel is pumped from a tank to the injector. The flow rate is controlled by the gear pump. Inside the injector, a surge chamber smoothes out the turbulence of the fuel. Then the liquid is pushed through the plane slit. The studied liquid is commercial Diesel oil, a dielectric liquid with a slight conductivity. The characteristics of this dielectric liquid at a temperature of 20°C are close to the kerosene ones and are presented in Table 1.

Table 1 Typical Characteristics of the Diesel Oil at 20 °C

Mass density	ρ [$kg.m^{-3}$]	850
Kinematic viscosity	ν [$m^2.s^{-1}$]	$4.3\cdot10^{-6}$
Electrical conductivity	σ [$S.m^{-1}$]	$1.15\cdot10^{-9}$
Relative permittivity	ε_r	2.2

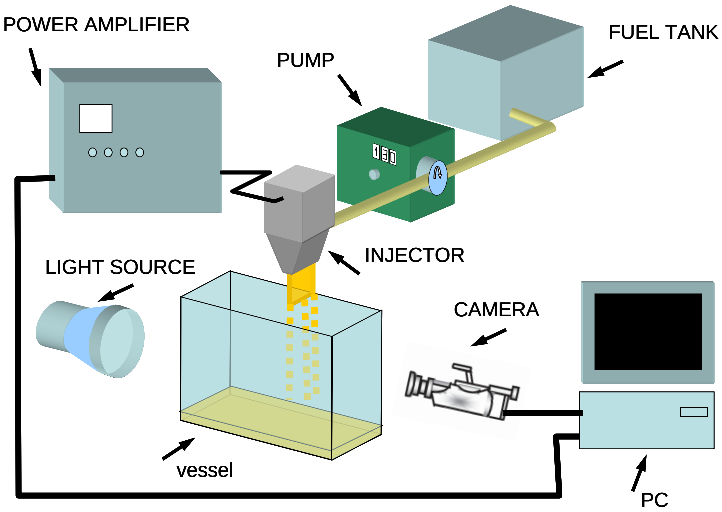


Figure 2 Experimental Setup

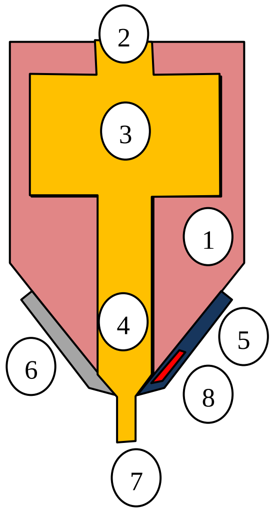
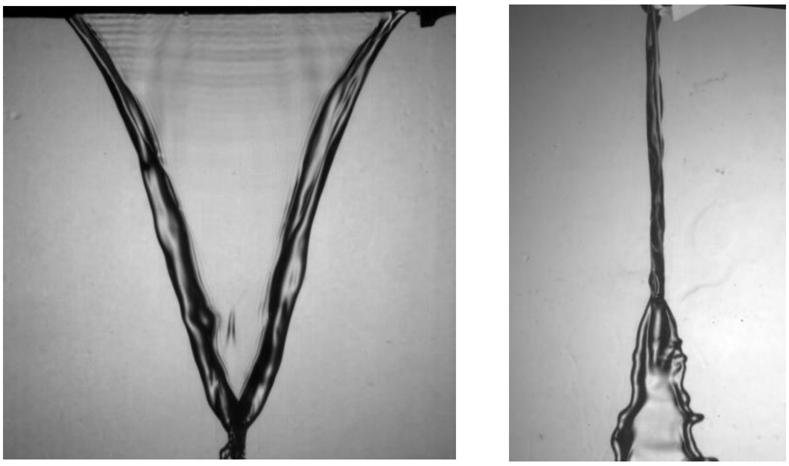


Figure 3 Schematic view of the injector

A schematic of the injector is proposed in Figure 3. It is mainly composed of the dielectric body (1). The fuel entrance is placed at the top of the injector (2). Before entering into the rectangular slit (4), the carburant pass through the surge chamber (3) in order to smooth the turbulence of the liquid. Two blades (5-6) are used as lips in order produce a 300 µm thick plane sheet (7). The actuator is mainly composed of two electrodes. The first one is the grounded blade of steel (6). The second one is a ribbon of steel (8) embedded into the second blade (5) and connected to the high voltage power supply. The blade (8) is inside the dielectric material. These electrohydrodynamic actuators are named Dielectric Barrier Injectors. They have been firstly proposed by [13-15]. The sheet is stable, when the EHD actuator is off (Figure 4).



(a) (b)

Figure 4 Shadow images of a plane sheet V_l = 1 m.s^{-1}. (a) front view, (b) side view

Figures 4a and 4b show the shadow images of the liquid sheet of Diesel oil obtained at a flow-rate 7.65 g/s in quiescent air. In the absence of electric perturbation, a typical triangular plane sheet bounded by two cylindrical rims flows out from the slit. The injector lips are visible as a black line at the top of the images. As a result of the surface tension the edges contract and the rims grow as they accumulate the liquid from the contracted sheet. Some very small disturbances are visible on the rims but they are not sufficient to induce the breakup of the liquid sheet. Because of the surface tension, the two rims draw together and impinge to form another sheet at right angle to the first (Figure 4b).

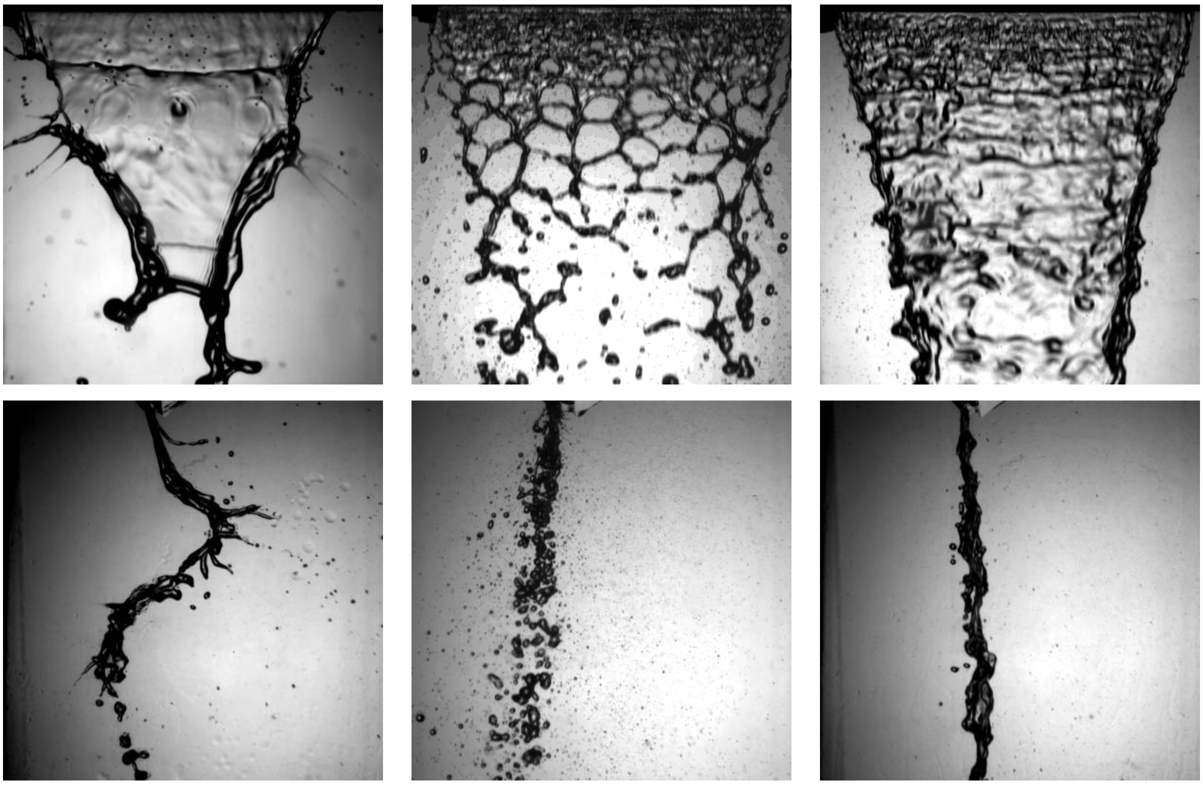
Modes of sheet disintegration

As it has already been demonstrated in [16], three atomization modes depending on experimental conditions could be observed. The first one is the flapping mode shown in Figure 5a. The liquid sheet motion could be compared to a flag motion. In this mode, a global streamwise oscillation with large amplitude is produce at the injector lips. The wavelength of these oscillations is important and the surface remains smooth The disintegration of the liquid sheet occurs far from the injector and the spray angle is very large. Stretched ligaments of liquids are ejected on the sheet edge but some also perpendicularly to the sheet. This second phenomenon is not currently understood but it could be due to Marrangoni's effect induced by surface electric charges.

The second mode is the perforated mode shown in Figure 5b. In this mode, primary oscillations of high frequency are generated by the EHD actuator. These oscillations have very high frequencies and are probably mainly composed of harmonics of the signal frequency. Afterwards, some holes appear in the sheet. Holes are bounded by rims which grow in size until the rims of adjacent holes coalesce to produce ligaments. The resulting shape looks like an irregular mesh or net. As the frequency is increased, these holes become more numerous and the net region begins to recede towards the injector lips. Finally, the ligaments break into droplets of varying sizes. This behavior seems to have some similarities with the perforated sheet mode described by Dombrowski and Fraiser [11] which is one of the three disintegration modes observed when studying the characteristic development of very thin liquid sheets of liquid from a single-hole fan nozzle at high Reynolds number.

The last mode is the disturbed mode presented in Figure 5c. This mode was not described in [16]. The liquid sheet is rough. High frequency oscillations are visible and it seems that spanwise and streamwise waves with low amplitudes agitate the sheet. As no oscillations are visible on the liquid sheet when the actuator is on, it is clear that these perturbations are induced by the electric charges injected at the electrode lips. In this mode, electric forces are too weak to induce the formation of ligaments. Surface tension forces remain greater than electric forces.

As shown in [16], the flapping mode is most often observed when the applied signal frequency is below 100 Hz whereas the perforated mode is visible above this value. The disturbed mode is a high frequency mode bit it seems that no direct relationship exists between the disturbed mode and the signal frequency. But the frequency is not the only parameter. Liquid sheet thickness, velocity, and viscosity are also very important parameters which will be exposed in another study.



(a) The flapping mode (b) The perforated mode (c) The disturbed mode

Figure 5 Shadow views of a sheet of Diesel oil, 300 µm thick and 6 cm wide, under electrical excitation

Influences of the signal shape

In order to study the influence of the signal shape on the liquid sheet, three shapes have been tested: square, sine wave, and triangle (Figure 6). Regardless of the signal shape, the observed mode of disintegration is always the flapping mode at low signal frequency. The frequency of the streamwise oscillation remains equal to the signal frequency.

However, below 20 Hz, the signal shape has a strong influence on wave shape. A sine wave signal produces a wave with a smooth surface. Perpendicular ligaments are few and the wave amplitude exceeds 1 cm. On the contrary, a square signal induces a rough wave surface with numerous perpendicular ligaments. The wave amplitude is larger than the one obtained with the sine wave signal. The oscillations produced with a triangular signal are a little bit more complex. The liquid surface remains smooth and it seems that no wave agitates the surface. In this case the liquid sheet is twisted by the electric forces and the amplitude of these perturbations is small.

The perforated mode appears between 40 and 100 Hz for all the signal shapes. In this case, photos are identical: presence of streamwise oscillations and perpendicular stretched ligaments. But a great difference is observed on the break-up length. It can be observed that the sheet is totally disintegrated in the middle of the photo for a square signal. With the sine wave signal the complete disintegration is visible at the bottom of the photo while it isn’t observable for the triangular excitation.

This means that the break-up length is about 3 cm for a square signal, 5 cm for a sine wave signal and is assumed to be 7 cm for a triangle shape.

Beyond 100 Hz, no differences are visible on the shadow photographs of the three signal shapes. The sheet is disintegrated by the electric forces and numerous droplets are produced. It can be observed that big droplets remains close to the sheet axis and small droplets are repelled far from this axis. This probably means that small droplets contain more electric charges than the big ones. Moreover, it is possible that some differences exist. A particle sizing study is currently conducted in order to compare the number and the size of the produced droplet and will be published in the near future.

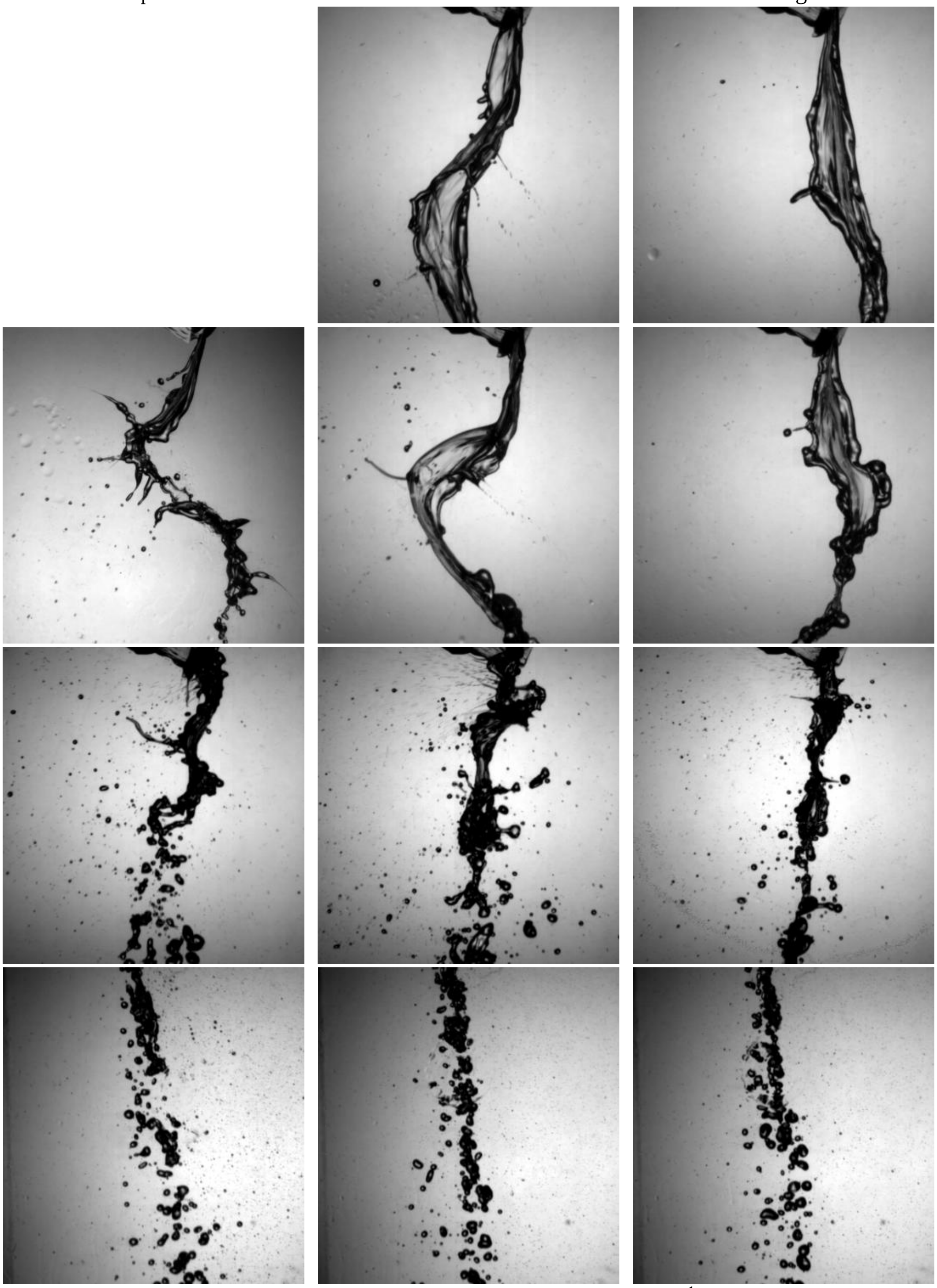


Figure 6 Side view of liquid sheet for various signal shapes and frequencies. $V = 1$ m.s^{-1}, signal amplitude 30 kV

All these observations confirm that the signal shape has a great influence on the sheet behavior. The square signal is the most effective signal to obtain the liquid sheet disintegration. However the sine wave excitation is very effective for large amplitude wave production at low frequency. It has already been proven that with an AC voltage, the charge injection mainly depends on signal slew rate. The fastest the slew rate, the more important the charge injection is. With the presented actuator, the liquid sheet atomization is correlated with the signal slew rate and then the quantity of injected charges.

It has also been demonstrated that the charge injection along a blade is more homogeneous when the signal slew rate is fast. Then the twisted movement observed under triangle excitation could be due to a non homogenous charge injection. This dissymmetry of charge injection could induce an irregular Coulomb force and then the sheet twists.

Influence of the signal amplitude

It has been proven that the signal shape and then the signal slew rate have a great influence on the liquid sheet disintegration. In this part, the study focuses on the signal amplitude. All experiments have been performed on a liquid sheet of 300 µm thickness, 1m.s^{-1} velocity. A square signal of 1 kHz frequency is applied to the embedded electrode. Under these conditions, an amplitude of more than 15 kV is necessary to observe an oscillation.

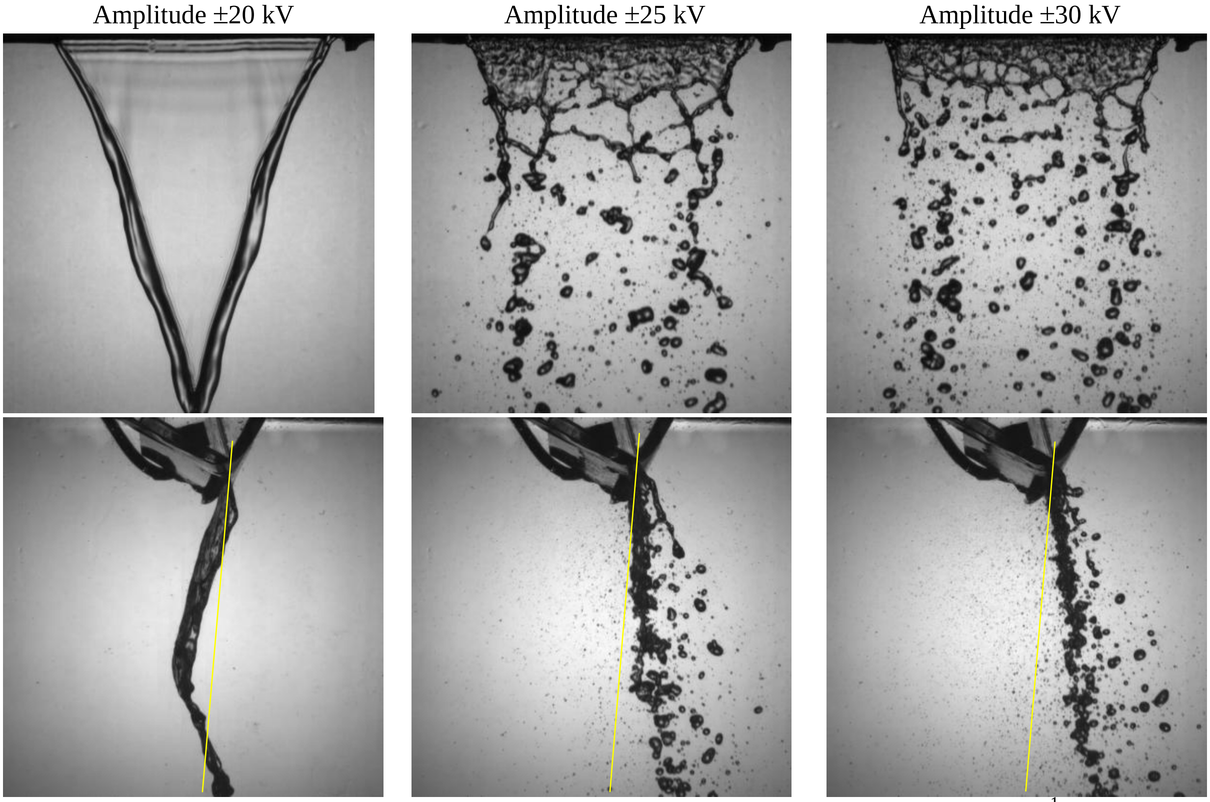


Figure 7 Views of liquid sheets for various signal amplitudes: f = 1 kHz, V = 1 m.s^{-1}

Some of the results are presented in Figure 7. The yellow line on the side views represents the sheet position in the absence of electrical excitation. At 20 kV amplitude, a few millimeters oscillation can be observed and the surface remains smooth. This result demonstrates that the flapping mode can be observed at high frequency.

The perforated mode appears at about 23 kV. In this mode, the signal amplitude modifies the sheet break-up length. The higher the amplitude, the shorter the break-up length is. Holes and then droplets become more numerous and smaller. There is a relationship between the velocity of the liquid sheet and the signal amplitude. For high liquid velocity, the disturbed mode was observed between 20 kV and 30 kV. It is well known that like the surface tension, inertial forces stabilize the sheet. Then, in order to obtain the sheet disintegration, the Coulomb force and then the signal voltage must be increased when the liquid sheet velocity is important.

Conclusion

This study is the second part of an experimental investigation conducted with a new electrohydrodynamic actuator for electrospraying applications. This EHD actuator is based on a dielectric barrier injection system which allows high electric field production while preventing the onset of spark. Experiments were carried out on thin sheets of commercial Diesel oil without active surface agent. The flow rate and the liquid sheet thickness are similar to the ones used in turbo engines. In contrary to typical air blast atomizer, the atomization is not obtained by the use of a shear air flow or any other form of mechanical disturbance but only with electric forces.

Three modes of disintegration have been observed: the flapping mode, the perforated mode, and the disturbed mode. The analysis of various signal shapes has demonstrated that square signals are more efficient to shake the sheet than the sine wave and the triangle one. The square signal produces a lot of stretched ligaments perpendicular to the sheet. A low frequency a sine wave signal could be use to obtain large amplitude streamwise oscillations. Finally, the sheet could be twisted when a triangle signal is applied to the device. This phenomenon may be due to non uniform injection at injector lips.

In addition, the influence of the signal amplitude is very important. At least 23 kV of signal amplitude must be applied in order to have a notable influence on the atomization. Similarly with the signal frequency, higher values of the applied amplitude allow to reduce the size of holes within the liquid sheet and consequently the diameter of atomized droplets.

In this work, a qualitative study has been conducted on the primary breakup of liquid sheet of fuel. A quantitative one will be conducted in the near future on the spray characteristics in order to complete this research.

References

[1] Mansour, A. and Chigier, N., *Disintegration of liquid sheets*. Phys. Fluids A 3: 2971–2980 (1990).

[2] Mansour, A. and Chigier, N., *Dynamic behavior of liquid sheets*. Phys. Fluids A 2: 706–719 (1991).

[3] Dumouchel, C., *On the experimental investigation on primary atomization of liquid streams*, Experiments in Fluids 45-3: 371–422 (2008).

[4] Bremond, N., Clanet, C., and Villermaux, E., *Atomization of undulating liquid sheets*, Journal of Fluid Mechanics 585 (2007).

[5] Larricq-Fourcade, C., Lavergne, G., Berthoumieu, P., and Thivet, F., *Improvement of Airblast injectors with electro-aerodynamic actuators*, 2nd International Symposium on Non Equilibrium Processes, Combustion and Atmospheric Phenomenon, 41-49 (2005).

[6] Boukra, M., Cartellier, A., Ducasse, É., Gajan, P., Lalo, M., Noel, T., and Strzelecki, A., *Use of Faraday instabilities to enhance fuel pulverisation in air-blast atomizers*, Comptes Rendus - Mecanique 337-6-7:492-503 (2009).

[7] Kelly, A.J., *The Electrostatic Atomization of Hydrocarbons*, J. Inst. Energy 57:312–320 (1984).

[8] Shrimpton, J.S. and Rigit, A.R.H., *Spray characteristics of charge injection atomizers with small orifice diameters*, Atomization and Sprays 16-4:421-442 C (2006).

[9] Berthoumieu, P. and Lavergne, G., *Video Techniques Applied to the Characterization of Liquid Sheet Breakup*, Journal of Visualization 4-3:267-275 (2001)

[10] Chigier, N. and Dumouchel, C., *Atomization of Liquid Sheets*, Prog. Astronaut Aeronaut 166:241-259 (1996).

[11] Dombrowski, N. and Fraser, R.P., *A photographic investigation into the disintegration of liquid s*heets, Phil. Trans. Roy. Soc. London A 247:101-130 (1954).

[12] Larricq-Fourcade, C., *Etude de la pulvérisation assistée en air d'une nappe liquide et influence d'un vent ionique sur les instabilités hydrodynamiques*, Thèse de Doctorat, École Nationale Supérieure de l'Aéronautique et de l'Espace (2006).

[13] Louste, C., Daaboul, M., and Romat, H., *A study of vortex shedding induced by dielectric barrier injection*, Journal of Electrostatics 67-2-3:348–353 (2009).

[14] Louste, C., Daaboul, M., and Romat, H., *Experimental study of a plane turbulent wall jet induced by a dielectric barrier injection in dielectric liquid*, IEEE International Conference on Dielectric Liquids 16:106-109, Poitiers, France (2008).

[15] Priol, L., Louste, C., and Romat H., *Experimental study of a dielectric barrier injection in Diesel oil. Measurements of liquid velocity by LDV*, ESA/IEEE Electrostatics Joint Conference:95–102 (2006).

[16] Louste, C., Daaboul, M., Traore, Ph., and Romat, H., *Experimental Study of electrical primary break-up of a thin sheet of dielectric liquid controlled by an ElectroHydrodynamic actuator*, ILASS – Europe 2010, 23rd Annual Conference on Liquid Atomization and Spray Systems, P 10. Brno, Czech Republic, September (2010)