Experimental Study of electrical primary break-up of a thin sheet of dielectric liquid controlled by an ElectroHydrodynamic actuator

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Abstract

This paper is an experimental study of the primary break-up induced by an ElectroHydroDynamic actuator. Experiments have been performed on thin sheet 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 conventional injectors the disintegration of liquid sheets or liquid jets into required droplets is mainly controlled by a centrifugal force or a high-pressure injection or a shear air flow or any other form of mechanical disturbance. In this article, the atomization is obtained by using only electrical forces. The liquid sheet produces by the injector is stable when the EHD actor is switched off. On the contrary it is 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.

Introduction

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 coflowing airstreams. Unfortunately, a high air velocity is needed in order to obtain a fine atomization. This is the main drawback of air blast atomizers. With an air velocity below 30 $m \cdot s^{-1}$ the atomisation is too weak for fuel ignition. 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. Moreover, when the air velocity is below 10m/s the sheet of fuel is not sprayed anymore.

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.

The second one is focused on active methods. The aim is to induce or excite the sheet instabilities by using actuators. Some actuator as plasma actuators are used to act on the air streams . Some others as piezo-electric , electrical actuators act directly on the liquid sheet.

In the present work, the sheet of fuel is directly destabilised and disintegrated by an electrohydrodynamic actuator.

A lot of studies have been performed on fuel electrospraying. The first experiments and modelizations have been made on simple pressure atomizer . These studies have been completed and fully modelized by Shrimpton . 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 electrical forces are superimposing to the mechanical ones in order to improve the atomization.

In this article 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 electrical forces produced by an electrohydrodynamic actuator. As there is no coflowing airstreams and as the fuel is injected at low pressure, the liquid sheet is stable when the EHD actuator is turned off. 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.

Experimental setup

In industrial air blast atomizers, the fuel is injected at low pressure through an annular slit. Such device produces a thin tubular sheet of fuel. This shape is very efficient for atomization but difficult to investigate. More than a decade of studies in atomization process has proved that mechanism of disintegration are similar on cylindrical and planar thin sheet of liquid . The present study has been made with a planar injector because of its simpler design and adaptability to optical techniques.

The liquid sheet is generated from a linear slit injector, which is 0.3 mm thick and 60 mm long. The liquid velocity is 1 m/s and it is assumed that the gas is at rest.

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The injector is made of PMMA which is a transparent dielectric material. The EHD actuator is placed at the injector lip. It is mainly composed of a stainless steel blade with a tip radius of 7 µm. The blade is connected to the high AC voltage source. The high voltage is supplied by a power amplifier TREK (±30 kV, 20 mA, 20 kHz) and a TTI waveform generator. The slew rate of the power supply is 400 $V{\cdot}\mu s^{-1}$.

The liquid used 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.

Fig.1 shows a schematic diagram of the experimental setup. 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 slit and a planar sheet is generated. In this study, the liquid velocity is maintained at $1 m{\cdot}s^{-1}$. The liquid Reynolds number base on liquid sheet thickness is $Re_{Liq} = 65$.

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

Mass density	ρ [$kg.m^{-3}$]	850
Kinematic viscosity	ν [$m^2.s^{-1}$]	$4.3{\cdot}10^{-6}$
Electrical conductivity	σ [$S.m^{-1}$]	$1.15{\cdot}10^{-9}$
Relative permittivity	ε_r	2.2

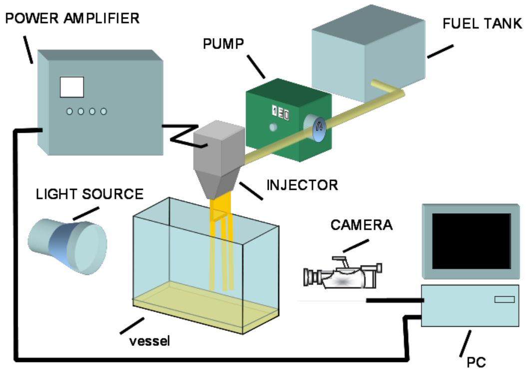
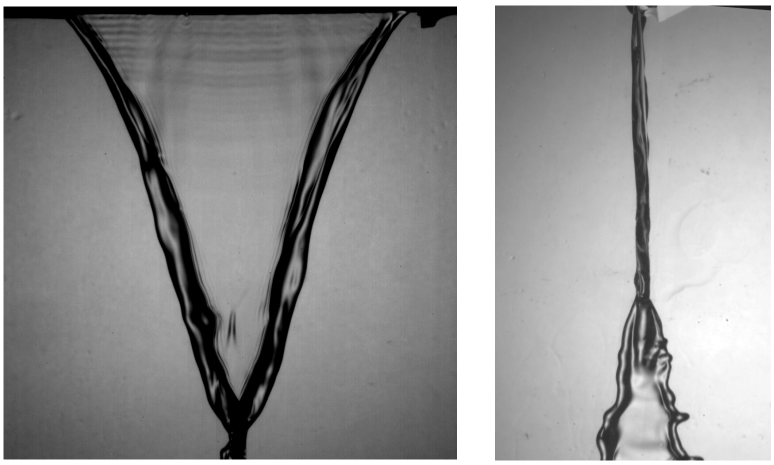


Figure 1. device

Experiments

Figures 2(a) and 2(b) show the shadow images of the liquid sheet of diesel oil obtained at a flow-rate 7.65 g/s in quiescent air. In absence of electrical perturbation, a typical triangular planar sheet bounded by two cylindrical rims flows out from the slit (Fig 2a).



(a) **(b)**

Figure 2. Shadow images of a planar sheet V_l=1 $m{\cdot}s^{-1}$. (a) front view, (b) side view

As a result of the surface tension the edges contract and the rims grow as they accumulate the liquid from the contracted sheet. Some 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 (Fig 2 b). This effect is repeated until a plain cylindrical jet is formed. Then this jet breaks into large drops.

From Fig 3, it's quite evident that the surface tension force, which consolidates the liquid surface, is unable to withstand the disruptive excitation produced by the EHD actuator.

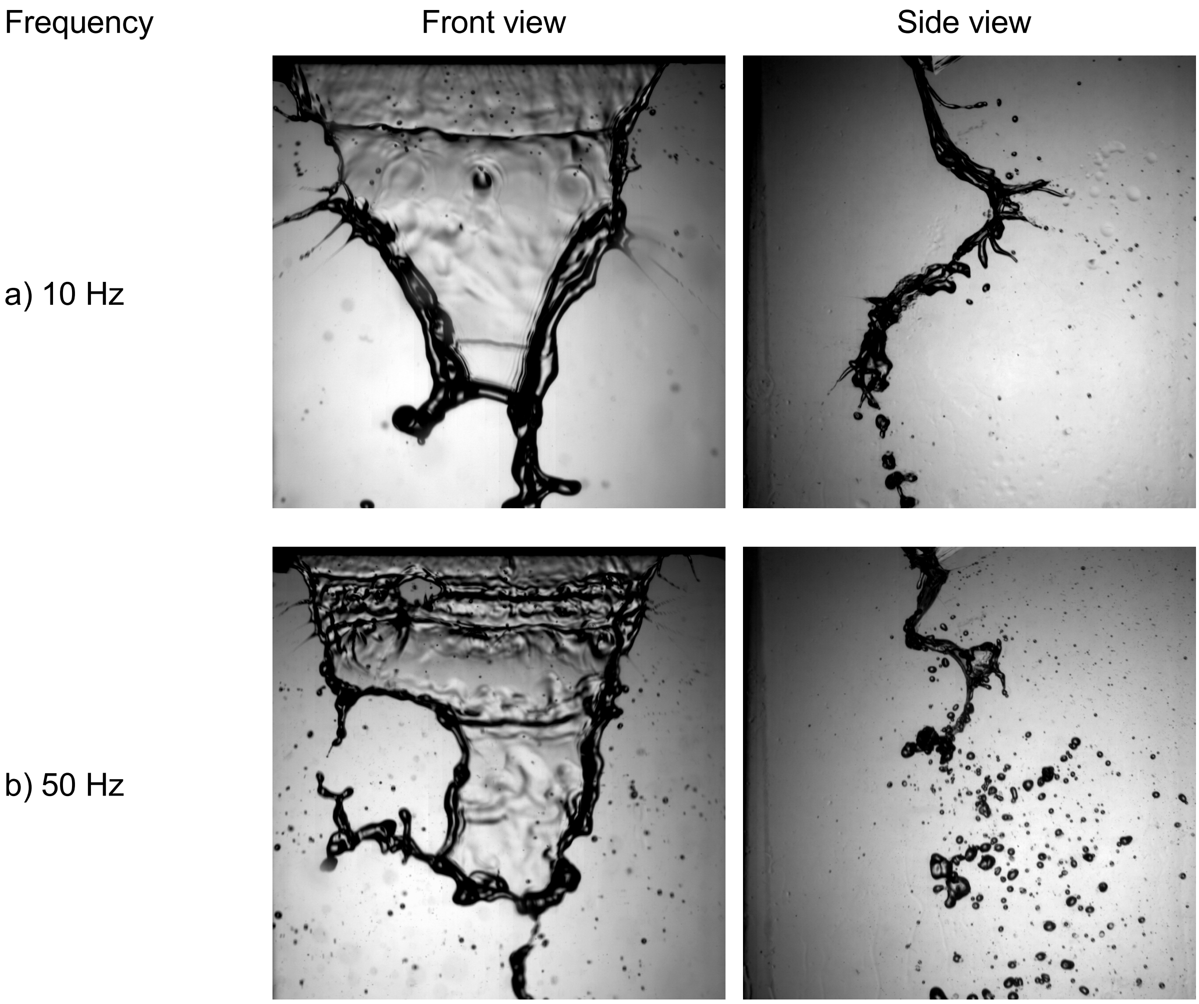
Depending on the signal frequency, two modes of sheet disintegration can be distinguished: a flapping mode and a perforated-sheet mode.

In the flapping mode, waves originate at the injector lips and develop in the streamwise direction with increasing amplitude. These global oscillations are not due to classical hydrodynamic instabilities as the Kelvin-Helmholtz instability or the Rayleigh-Taylor instability but are produced by the EHD actuator. The wave frequency is equal to the signal frequency and easy to control (Fig 3b, 3c, 3d).

In the perforated mode, the disruption of the sheet is mainly controlled by the appearance of holes which perforated the sheet (Fig 3d, 3e). The wavy mode is dominant when the signal frequency is below 50 Hz (Fig 3b) whereas the perforated mode is determinant beyond 250 Hz.

The flapping mode

In a pure flapping mode, the sheet is disintegrated far away from the injector. A global streamwise oscillation is induced by strong Electrical forces generated at the injector lips. The oscillation amplitude depends on the signal frequency. It is about 2 cm at 10 Hz (Fig 3 b side view), 8 mm at 50 Hz (Fig 3c side view), and less than 5 mm at 100 Hz (fig 3d side view). It is difficult to obtain a flapping mode at a high frequency. Below 10 Hz, the electrostatic repulsion of electrostatics charges injected by the EHD actuator generated violent local perturbations which disintegrate the edge rims (Fig 3a and 3b front view) or perforate the sheet (Fig 3b).



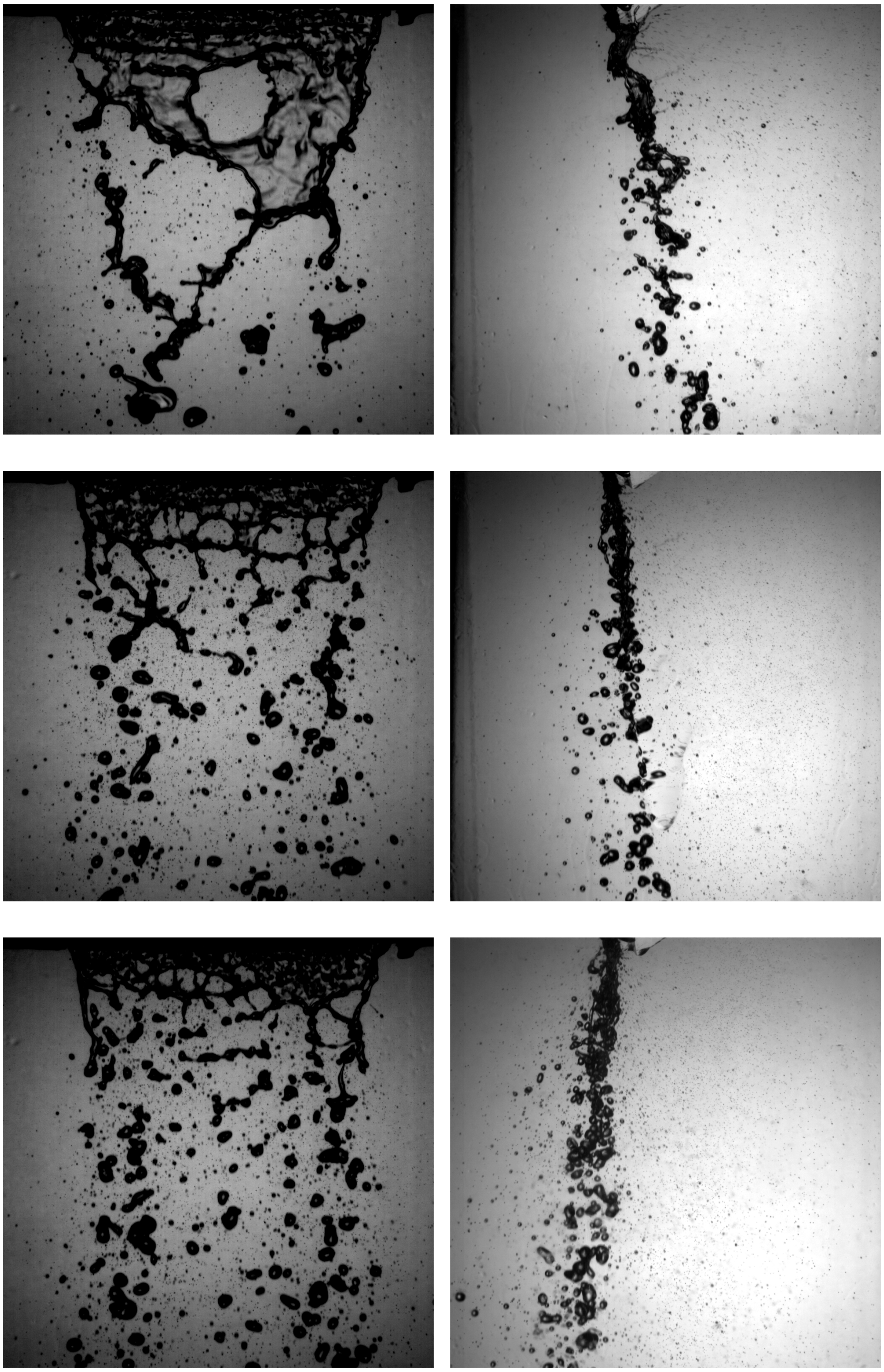


Figure 3. Shadow views of a sheet of diesel oil under electrical excitation from an AC signal of various frequencies (a-b-c-d-e)

The perforated mode

In the perforated mode, the liquid sheet disintegration is the result of four successive phenomena which occur in four successive regions of sheet Fig 4. Firstly, close to the injector lips a primary oscillation of high frequency is generated. This primary oscillation is produced by the EHD actuator. The frequency of this oscillation is very high and is probably equal to the signal frequency. Secondly, some holes appear in the sheet. This is the perforated region. The holes are bounded by rims. They grow in size until the rims of adjacent holes coalesce to produce ligaments. The resulting shape looks like an irregular mesh or net (the net region). Finally, the ligaments break into drops of varying size. This behavior seems to have some similarities with the perforated-sheet mode described by Dombrowski and Fraiser 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.

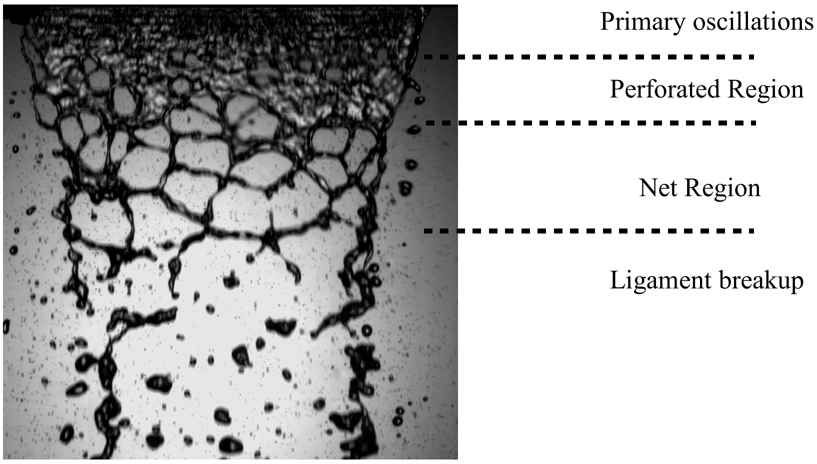
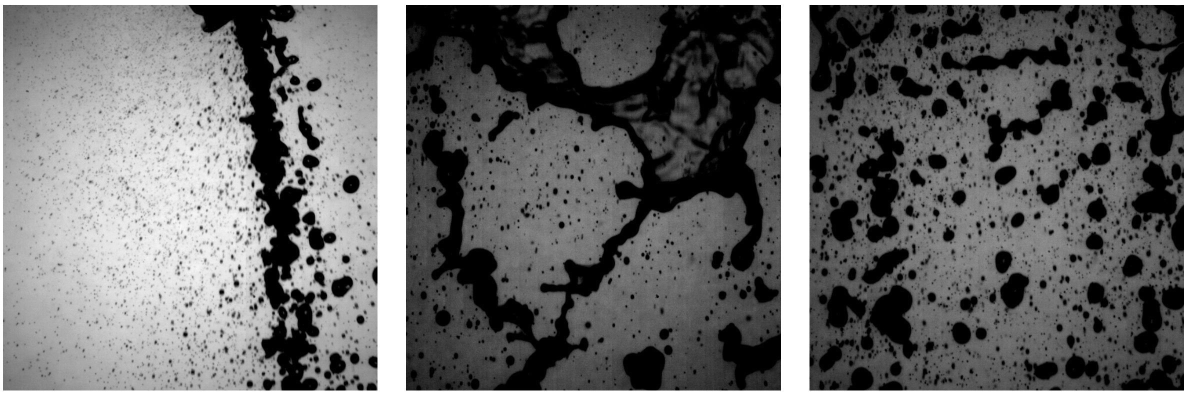


Figure 4. Shadow image of the planar sheet V_l=1 m·s^{-1}, f = 250 Hz

As it has been already mentioned, a high frequency disturbance is caused in the sheet by the EHD actuator at the injector lips. As the frequency is increased this disturbance becomes more violent and the region of primary oscillation begins to recede towards the nozzle. In the same way, an increase of the signal frequency increases the number of hole in the perforated region and then the size of the meshes in the net region. As a consequence, when the frequency is increased, the rims become thinner and start to disintegrate at an early stage.

Origin of drop

In both modes of disintegration a wide range of droplet size, from a few microns to a few millimeters, is obtained. A lot of small droplets are produced close to the injector lips (Fig 5a). They spread rapidly in the perpendicular direction of the sheet. As these droplets are visible through the holes it is assume that they are not resulting of the rims disintegration (Fig 5b). After the disintegration of the meshes of the net a wide range of droplet can be observed (Fig 5c).



(a) **(b)** **(c)**

Figure 5. Shadow images of the droplet at various positions from the injector lips

Two distinct phenomena of droplet production have been identified.

The first atomization mechanism is the production of stretched ligaments. These stretched ligaments are visible in all disintegration modes. They are generated on the edge of the sheet as well as on the surface of it. When they appear on the edge they are stretched in the same plane than the sheet (Fig 6 ①) but when they emerge from the sheet surface they are stretched right to the sheet (Fig 6 and Fig 7 ②). These ligaments are created by the electrical charges injected in the liquid sheet by EHD actuator. The electrical charges of the same polarity repel each other and generate these stretched ligaments. This mechanism produces extremely small droplet ranging from less than 10 μm to 100 μm.

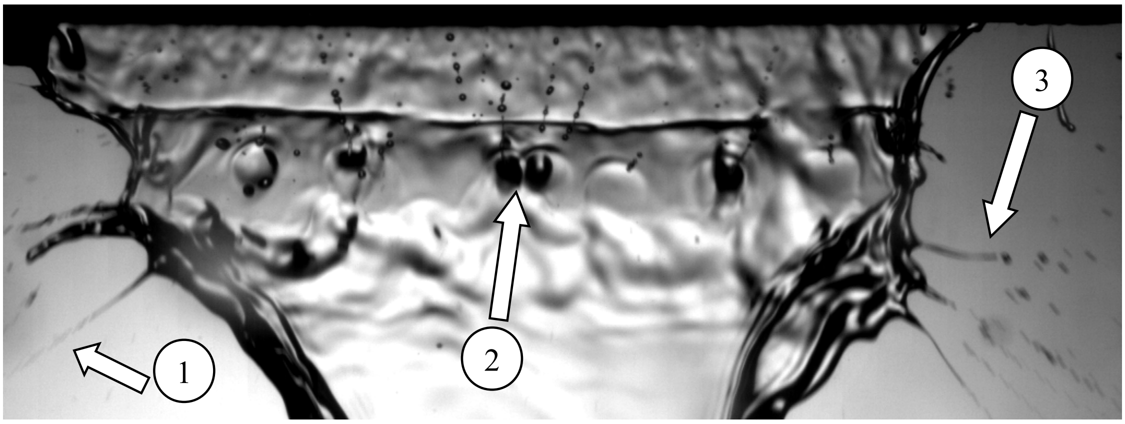


Figure 6. Stretched ligaments: ①on the sheet edge, ②perpendicular to the sheet

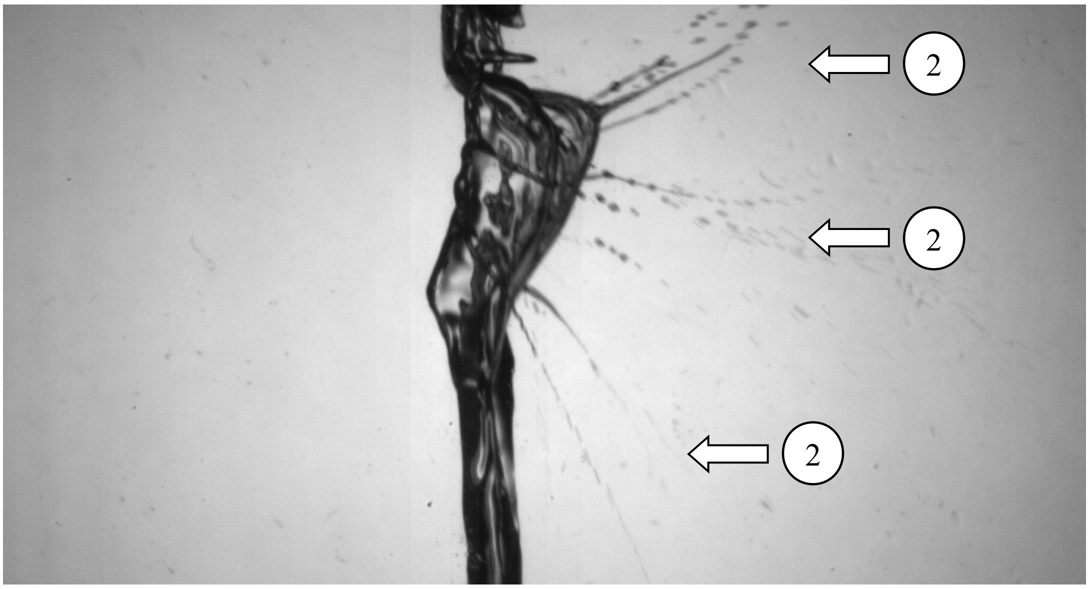


Figure 7. Stretched ligaments perpendicular to the sheet

The second source of droplet is the net disintegration. According to the Plateau-Rayleigh instability a free column of liquid is unstable if its length is greater than the perimeter of the cylinder. Unfortunately the threads of the net which are non uniform in diameter produce non uniform drops (Fig 8 ①). Moreover, it is also visible in (Fig 8 ②) that the threads are connected in trees and the connecting points look like shapeless bags of liquids. These bags disintegrate in a wide range of drop sizes. The largest drops are produced via this mechanism. As the surrounding gas is at rest, the Weber number of these large droplets remains low even if the diameter is greater than few millimetres. They are stable and no secondary atomisation can be observed.

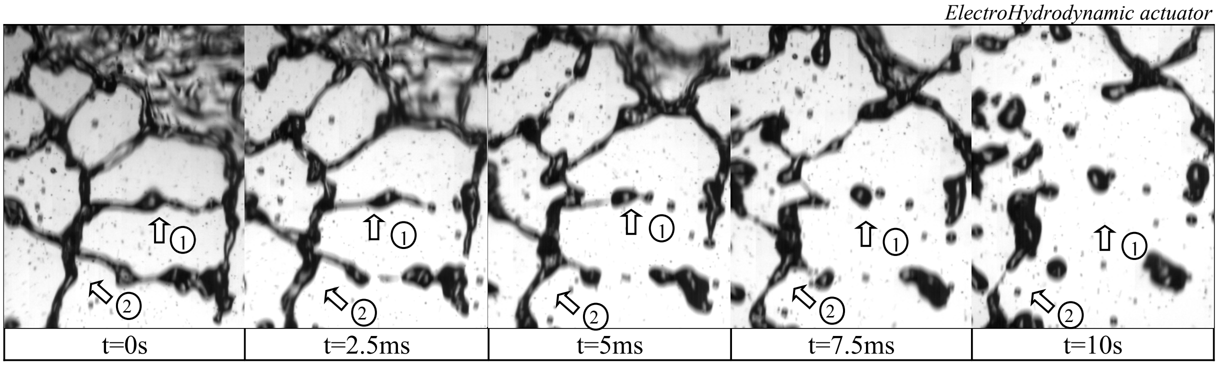


Figure 8. Treads disintegration (Evolution in time)

Conclusion

It is well known that a conductive liquid can be fully atomized by electrical forces. Most of experimental studies on electrospraying have been performed with conductive liquids. The problem is more complicated in the case of dielectric liquids especially because it is more difficult to inject an important quantity of electric charge in the core of liquid. For this reason, most of studies on dielectric liquid atomization are performed at very low flow rate or by superimposing a mechanical disturbance. In this work, it is proved that a thin sheet of fuel can be atomized by a new EHD actuator. Electrical forces induce the breakup of the sheet without any additional forces even if the flow rate is equal to the one used in industrial injector. The experiments have demonstrated that two modes of disintegration can be obtained: the flapping mode and the perforated-sheet mode. Both disintegrating mode are fully dependant of the signal frequency and so, easy to control. Moreover, some typical parameter of atomisation as the breakup distance can also be controlled by the signal frequency.

A wide range of droplet size diameters is produced by the proposed device. The droplets originate from two distinguish phenomena. The first one is purely electrical and produces very small droplets via the creation of stretched ligaments. The second one is a more common hydrodynamic phenomenon that produces large scale of droplet.

In future works, the effects of the signal frequency will be quantified and the electrical parameters will be optimized in order to minimize the maximum size of the droplet.

References

[1] Mansour, A., Chigier, N., 1990. Disintegration of liquid sheets. Phys. Fluids A 3, 2971–2980.
[2] Mansour, A., Chigier, N., 1991. Dynamic behavior of liquid sheets. Phys. Fluids A 2, 706–719.
[3] C. Dumouchel, On the experimental investigation on primary atomization of liquid streams, Experiment in Fluids 45 (3) (2008) 371–422.
[4] N. Bremond, C. Clanet, E. Villermaux, Atomization of undulating liquid sheets, Journal of Fluid Mechanics 585 (2007).
[5] Larricq, G. Lavergne, P. Berthoumieu, F. Thivet, *Improvement of Airblast injectors with electro-aerodynamic actuators*, 2nd International Symposium on Non Equilibrium Processes, Combustion and Atmospheric Phenomenon, p 41-49, 2005.
[6] Boukra, M., Cartellier, A., Ducasse, É., Gajan, P., Lalo, M., Noel, T., Strzelecki, A. , Use of Faraday instabilities to enhance fuel pulverisation in air-blast atomizers, Comptes Rendus - Mecanique 337 (6-7), pp. 492-503, 2009.
[7] A.J. Kelly, *The Electrostatic Atomization of Hydrocarbons*, J. Inst. Energy, vol. 57, pp. 312–320, 1984.
[8] J.S. Shrimpton, ARH Rigit, *Spray characteristics of charge injection atomizers with small orifice diameters*, Atomization and Sprays, 16, 4, 2006, p421-442 C.
[9] Berthoumieu, P., Lavergne, G., Video Techniques Applied to the Characterization of Liquid Sheet Breakup Journal of Visualization 4 (3), pp. 267-275, 2001.
[10] Chigier N. and C. Dumouchel, Atomization of Liquid Sheets, Prog. Astronaut Aeronaut, vol 166, pp241-259 1996.
[11] N. Dombrowski and R. P. Fraser (1954), A photographic investigation into the disintegration of liquid sheets, Phil. Trans. Roy. Soc. London A, 247, pp. 101-130.