Polarity Inversion in EHD Spraying

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A study of polarity inversion effects in EHD spraying is developed by characterizing the several atomization regimes that can be observed by varying liquid flow rate and applied voltage. An experimental approach is adopted. N-heptane, doped with an antistatic additive, is atomized in a classical needle-to-plate system. Study of polarity effects is essentially based on the comparison between two-dimensional maps of the stability regimes occurring by varying the controlling parameters. Direct visualization by digital camera has been used for this purpose. Furthermore a quantitative validation of the maps has been obtained by matching spray images with laser PDA system measurements, providing informations on droplet size and velocity. Results show that occurrence of the regimes is not qualitatively influenced by polarity inversion, but when negative polarity is imposed to liquid, any modifications on spraying modes need higher variations in applied voltage, and so the regimes are stable in larger voltage ranges. Availability of a valid atomization in negative polarity, most of all in conditions interesting for combustion applications, such as multi-jet mode, could solve problems due to the loss of atomization quality observed when positively charged sprays interact with flame. Negative polarity widens the spectrum of ways by which an active control on spraying process, in order to prevent combustion instabilities, could be realized.

1. Introduction

Traditional atomizers operate on liquid breakup mechanisms by supplying energy, often using a subsidiary gas flow, or mechanic energy, by means of moving or vibrating devices. These systems allow to obtain fine and monodisperse sprays, but the atomization process is not very efficient, being a large part of the supplied energy retained by the drops as kinetic energy.

Higher efficiencies may be reached by EHD atomization. The first effect of charge injection is the jet striction, through a mechanism first modeled by Taylor [1]. This striction reduces the jet diameter so that the diameter of the droplets formed during the jet break-up is reduced accordingly. In addition, applied voltage induces an intensification of varicose instabilities and gives rise to kink instabilities that promote a better liquid disruption (Cloupeau and Prunet-Foch [2], Son and Ohba [3]). If the droplets are injected in a high temperature region the evaporation increases charge-to-mass ratio and, if the *Rayleigh limit* for the surface charge is reached, the droplet can undergo a secondary breakup producing an even finer spray. Moreover, because of electrostatic repulsion among charged droplets, the coalescence is reduced to a minimum and the spray angle is increased allowing for the realization of a good dispersion of liquid in the gas phase.

Interaction among force induced by the presence of electric field and the other active forces - inertia, gravity, surface tension and viscosity - is responsible of the wide variety of spraying conditions that can be observed by modifying liquid flow rate and applied voltage. That variety suggested to study polarity inversion effects by comparing atomization conditions through stability maps obtained in either positive or negative polarization conditions, such as those presented by Cloupeau and Prunet-Foch [2][4], Jaworek and Krupa [5] and Ragucci *et al.* [6].

Images collected by a digital camera, with a sufficient time resolution, can provide a first identification of the spraying mode. In this paper results obtained by means of direct spray visualization have been compared with quantitative information on droplet size and velocity, measured by using a PDA system. The systematic comparison of the result of the two techniques allowed an unambiguous identification of the atomization regimes and of their characteristic droplet size distributions. It is interesting to note that the PDA systems have been largely used in the characterization of EHD sprays (Gomez [7], Hartmann *et al.* [8]), but never for a systematic characterization of the spraying modes.

Previous studies on combustion of positively charged liquids have shown that the presence of flame significantly reduces the atomization quality. This fact could be due either to heat transfer phenomena and to the interaction between the electric charges on droplets and the electric charges normally observed in flames. In particular it is possible to suppose that radical species, formed in the combustion process, induce a neutralization of droplet charge. One of the motivations of the present study on the effects of polarity inversion on EHD atomization is to verify whether negative polarity can obviate to charge neutralization. Another reason of interest for polarity inversion is related to the possibility of realizing an active control of the atomization process. A modulation of some spray properties, such as droplet size or spray angle, could indeed reduce or prevent the instabilities typically observed in several combustion systems.

2. Experimental setup

The configuration adopted for the atomizer is the needle-to-plate scheme, showed in fig. 1a. An electric potential of several kilovolts is applied between the needle, used to supply the liquid, and a metallic plate placed 3 cm below the tip of the needle. The stainless steel needle inner diameter is 0.25 mm and the outer one is 0.4 mm. The capillary is shielded by an insulating cylinder and supported by a coaxial plexiglas prism, bound to a micrometric moving device. The metallic plate is placed in a basin for liquid recovering. In the central zone of the plate many small holes have been made in order to prevent liquid stagnation on the metallic surface. The whole system has been insulated from external aerodynamic and electrostatic perturbations. To this purpose a cylindrical plexiglas shield and a coaxial iron mesh, kept floating, have been used.

Atomized liquid is n-heptane doped with 0.5% vol. of Stadis® 450 to enhance electric conductivity without significantly affecting other properties, such as surface tension, permittivity and viscosity. Electric conductivity of doped n-heptane is $6.76 \cdot 10^{-7}$ $(\Omega m)^{-1}$. A peristaltic pump provides for liquid feed. The flow rate operating range has been chosen between 10 and 55 cc/h. High voltage, up to 10 kV, is applied to the needle and the plate. Polarity inversion is simply possible by exchanging terminals. It has been assumed, according to the generally accepted nomenclature, that when the positive potential was applied to the needle the condition was identified as "positive polarity" and when the positive potential was applied to the plate it was identified as "negative polarity".

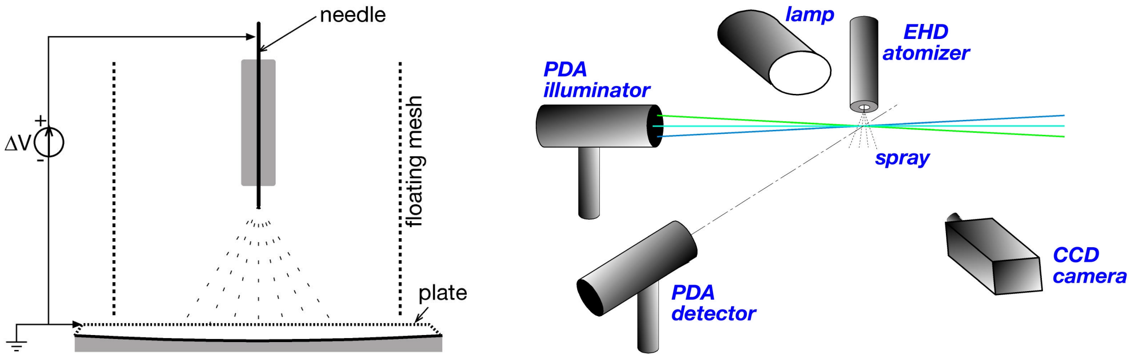

Fig. 1 Needle-to-plate configuration **(a)** and diagnostic setup **(b)**

All the experimental tests were conducted at atmospheric pressure and ambient temperature.
A schematic representation of the diagnostic setup is presented in fig. 1b.
A visualization system was used for qualitative characterization of the atomization regimes. A Pulnix TM-6710 digital camera, with resolution equal to 640x480 pixels, and a halogenous lamp realized a configuration similar to a flash shadowgraph system. A National Instruments IMAQ PCI-1422 acquisition board installed on a PC collects images of the spray. The system was able to acquire images up to 240 Hz, shutter time being fixed to 1/32,000 s. A Labview procedure was used to acquire and store the images for subsequent elaboration. In order to increase the readability of the images they were subtracted to a previously collected background image and then inverted. This produced images in which the liquid structures appears as black figures on a white background allowing for an easy identification of their morphology.
A laser PDA system by Dantec was used for quantitative characterization of the spray. It indeed allowed to collect detailed single point measurements of the distributions of droplet size and of two components of their velocity. PDA measurements have been all collected at a distance of 6 mm from the tip of the capillary, on the needle axis every time it has been possible. For oscillating-jet mode and precession mode data have been acquired on both needle axis and spray boundary. A 100,000 droplets sampling and a limit acquisition time of 1000 s for each measurement have been fixed in order to obtain distribution histograms statistically representative of the spray. Presence of hysteresis effects imposed to choose a strict experimental procedure: for each test liquid flow rate was parametrically fixed and voltage progressively increased from zero up to 10 kV.

3. Results

Each regime has been identified through spray images collected by the digital camera and quantitatively characterized by means of size and velocity data acquired by PDA system. Individuation of regime stability fields have made it possible to elaborate maps of occurrence, for both positive and negative polarities. The case of positive polarity will be extensively presented in the following sub-section. The negative polarity will be then discussed outlining the main similarities and differences with the positive polarity case.

For every chosen flow rate, *dripping mode* is observed when no voltage or low (under about 2.0 kV) voltage is applied. Liquid flows drop by drop from the tip of the capillary. Meniscus takes a hemispherical shape because of the effect of the surface tension. Liquid accumulation increases the hanging droplet's size, until gravity and electric field make it detach from the meniscus. It is noteworthy that surface tension causes a compression of the detached droplet

in the axial direction: oscillations occur between compressed and elongated shape and are progressively damped by dissipative mechanisms.
Voltage increases emission frequency of liquid fragments and reduces droplet size. Flow rate doesn’t influence significantly the balance of forces on the drop surface, so that it modifies only the emission frequency, according with mass conservation. Above a certain value of applied voltage, sibling droplets phenomenon is observed, i.e. the thin thread, linking up the hanging drop and the meniscus, generates itself a droplet, much smaller than the main one. This small droplet is quickly removed from the needle axis because of the electrostatic repulsion with the main drop.
For every flow rate value, a voltage increase bring to the stabilization of *spindle mode*, already described by many authors [2][5]. Voltage induced forces cause the elongation of a jet from the meniscus, but they are not enough strong to overcome capillary ones with push the liquid to assume spherical shape again. As a consequence an oscillating behavior set up with the periodical expulsion of a tiny jet and of an larger elongated liquid structure, named *spindle*, from the needle. The spindle, after its detachment, origins one or more large droplets, while the liquid jet breaks up forming a fine aerosol. Since the interest was biased toward the determination of size distribution of smaller droplet and the size of larger droplets could be easily estimated by the analysis of collected images, the PDA system was configured to measure the lower range of droplet sizes spectrum. The large drops originated by the spindle exceeds the PDA system higher size limits, so that collected measurements are only relative to the droplets formed during the break up of the jet and, hence, reports relatively small diameters. In short, in *spindle mode* spray quality is limited by the presence of large drops carrying away a not negligible amount of liquid flow rate. At higher voltage values kink instabilities occur. Little oscillations, around the needle axis, take place, so that spray appears more irregular and size distribution becames wider.

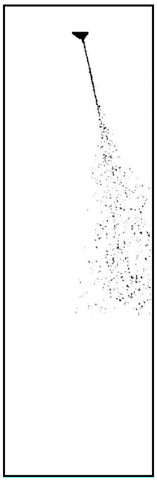

Fig. 2 Typical image of the Taylor cone-jet taken at liquid flow rate of 10 cc/h for an applied voltage of 3.3 kV.

In the low flow rate field, below 15 cc/h, in the voltage range between 3.2 and 3.8 kV it is possible to observe the well-known *Taylor cone-jet mode*. In this condition, which is reported in Fig. 2, the meniscus takes a conical shape, according to Taylor’s theory on equilibrium between capillary and electrostatic pressure. This fact causes a considerable striction of the emitted jet, so that its breakup generates a very fine spray, with very narrow size distributions and drop diameters lower than 10 µm. PDA data are presented in Fig. 3. Histograms represent droplet size and velocity distributions. For diameters, each histogram class is 2 µm wide; for velocities 10 cm/s. The velocity distribution too appears very narrow indicating the occurrence of a very ordered atomization process.

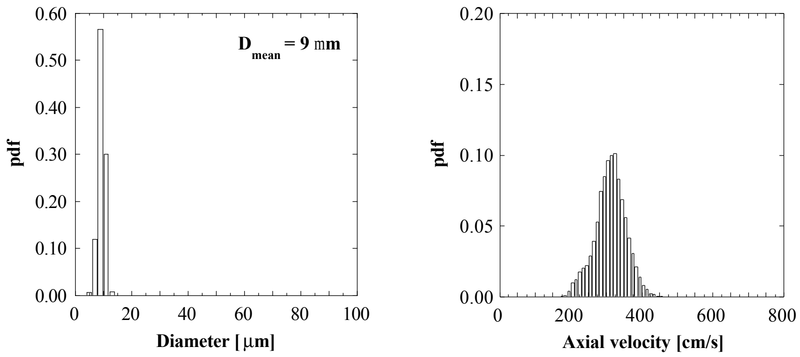

Fig. 3 Distribution functions of droplet size and axial velocity component for the *Taylor cone-jet mode* (Q = 10 cc/h, V = 3.3 kV).

For voltage values lower than 3.2 kV a continuous cone-jet cannot settle. In this case the extruded jet appear intermittently. This atomization regime is generally named *pulsed Taylor cone-jet mode*. PDA data indicate that in this condition the size distribution function is wider than in the Taylor cone mode. This is probably due to the jet intermittency which give rise, during the transient phase, to the formation of larger droplets. Also the axial velocity distribution appears wider and extends toward the higher velocities range, probably due to the higher velocities of the larger droplets.

In the same voltage field, a flow rate increase give rise and enhance kink instabilities that make no longer possible the stabilization of a cone-jet. Above about 15 cc/h two spraying modes are observed, in dependence of the applied voltage: the *oscillating-jet mode* and the *precession mode*, that are continuous and characterized by strong oscillations around the capillary axis.

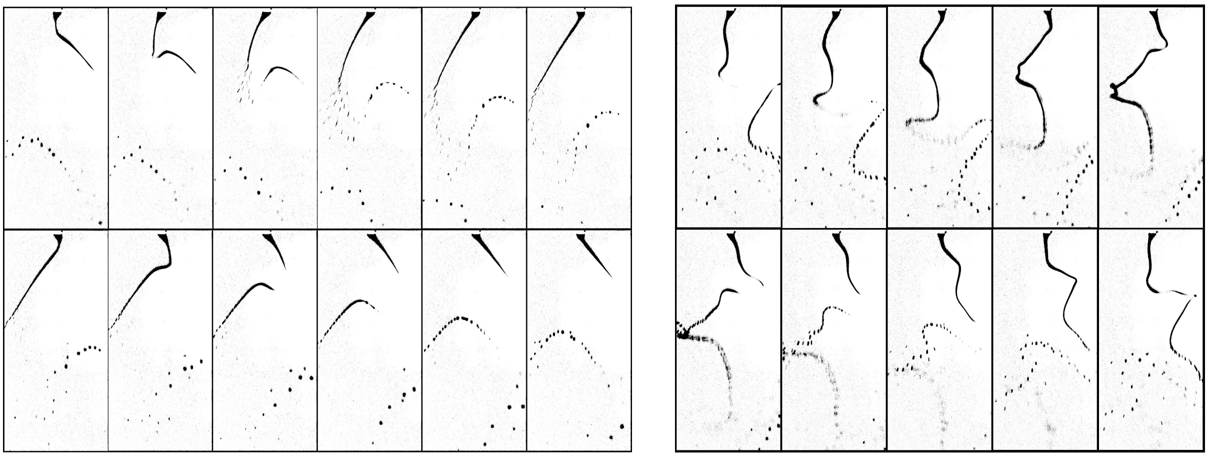

Fig. 4 Sequence of images of the jet in *oscillating mode* **(a)** taken at liquid flow rate of 35 cc/h for an applied voltage of 3.3 kV, and in *precession mode* **(b)** taken at liquid flow rate of 55 cc/h for an applied voltage of 4.6 kV.

An image sequence typically observed in the oscillating jet mode, that can be observed at lower applied voltage values, is shown in Fig. 4a. In this regime the jet oscillates in a plane containing the capillary axis, generating a plume of droplets with an ellipsoidal cross section, resembling the one typical of fan sprays.

Irregular thickness and shape of the jet cause large size and velocity distributions, mainly in the center of the spray, as it is showed by PDA measurements presented in Fig. 5. PDA measurements in this atomization condition often show polydisperse size distributions. Far from the center distributions are monodisperse, but droplets are however quite large.

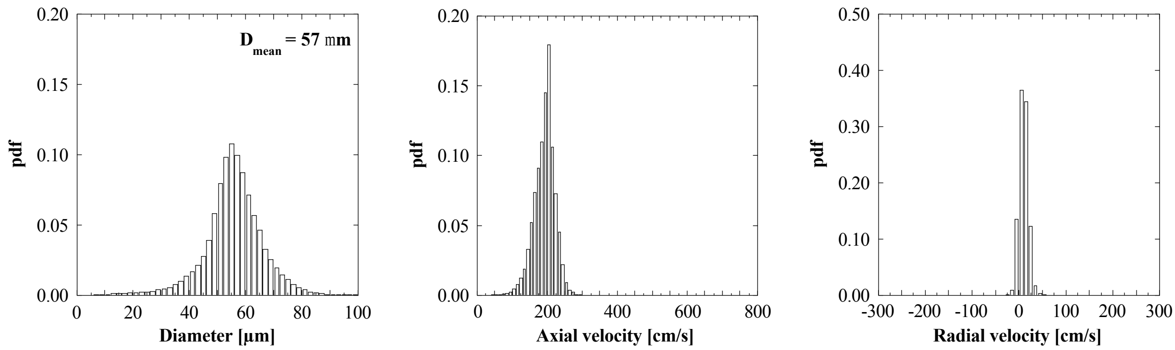

Fig. 5 Distribution functions of droplet size, axial and radial velocity components for the oscillating-jet mode (Q = 35 cc/h, V = 3.3 kV).

At higher voltage values in the low liquid flow rate range the oscillating mode become unstable and a precession motion is superimposed to the oscillating one. This mode can be named as precession mode. The composition of oscillation and precession movements generates a hollow cone spray (Fig. 4b). Because of jet dynamics, liquid emission takes place only in the periphery of the spray, so that in the center there are just few small, monodisperse droplets, pushed out by electrostatic repulsion, as indicated by PDA measurements. Data collected at a radial distance of 3 mm from the capillary axis, reported in Fig. 6, show the simultaneous presence of both small and larger droplets in the spray periphery.
The oscillating jet mode is no longer observed at liquid flow rates higher than 3.5 kV, due to the prevailing effect of kink instabilities that generates the precession motion.

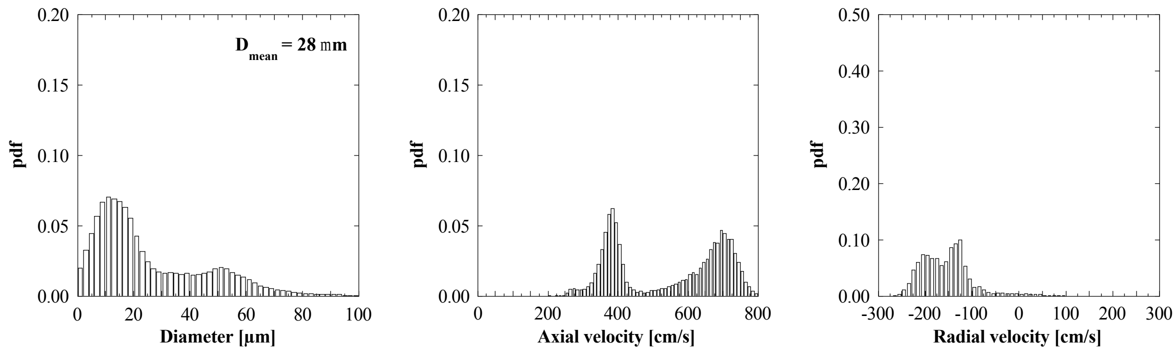

Fig. 6 Distribution functions of droplet size and axial and radial velocity components for the precession mode (Q = 55 cc/h, V = 4.6 kV, r = 3 mm)

For each flow rate, above a certain value of the applied voltage, jet striction effects are so strong that a single jet cannot carry off the supplied amount of liquid. In this condition the jet divides in two or more streams and meniscus flatten. This condition is commonly named *multi-jet regime*. The additional jets are, in general unstable at lower and stabilize progressively at increasing the applied voltage originating a steady multi-jet condition.
Electrostatic repulsion between the jets operates in centrifugal way, so that jets appear disposed on opposite sides of the flattened meniscus. Further voltage increases induce a progressive growth in the number of jets. Transitions are characterized by a fast change of the number of jets formed. A comparison between spray images and PDA data (presented in fig. 7) indicates that each jet behaves much like an insulated Taylor cone-jet. In fact, drop size distributions is reasonably monodisperse, with mean diameters lower than 10 µm. On the

contrary, the distribution of axial components of the velocity is much more wide than the one observed in the Taylor cone regime, probably due to the dragging effect of the electric field on the droplets. In the Multi-jet condition the radial velocity components are appreciable due to the orientation of the emerging jets.

On the ground of the close comparison of the results obtained by using both the visualization system and the PDA, that have been summarized above, it was possible to draw a stability map for each imposed polarity (reported in Fig. 8). In the map the regions, in a flow rate - applied voltage dominion, where the different atomization regimes were observed, are reported. In essence, it can be stated that, at least from a qualitative point of view, the same spraying modes could be observed in the two polarities.

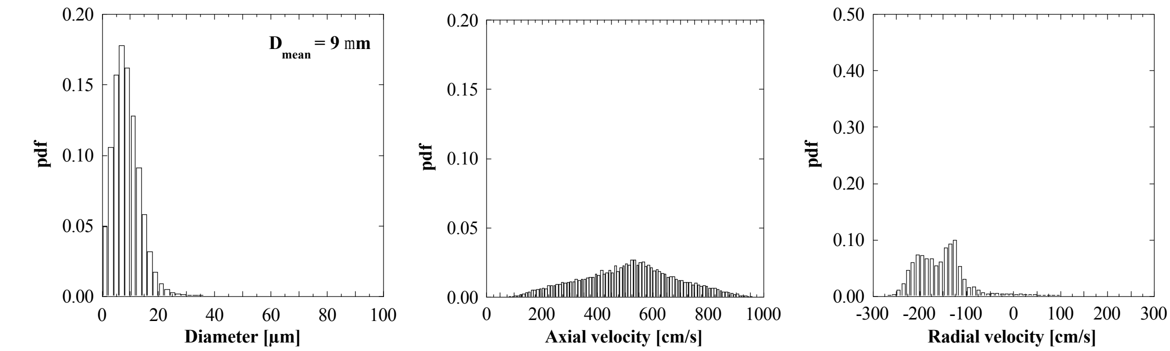

Fig. 7 Distribution functions of droplet size and axial and radial velocity components for the multi-jet mode (Q = 25 cc/h, V = 6.0 kV).

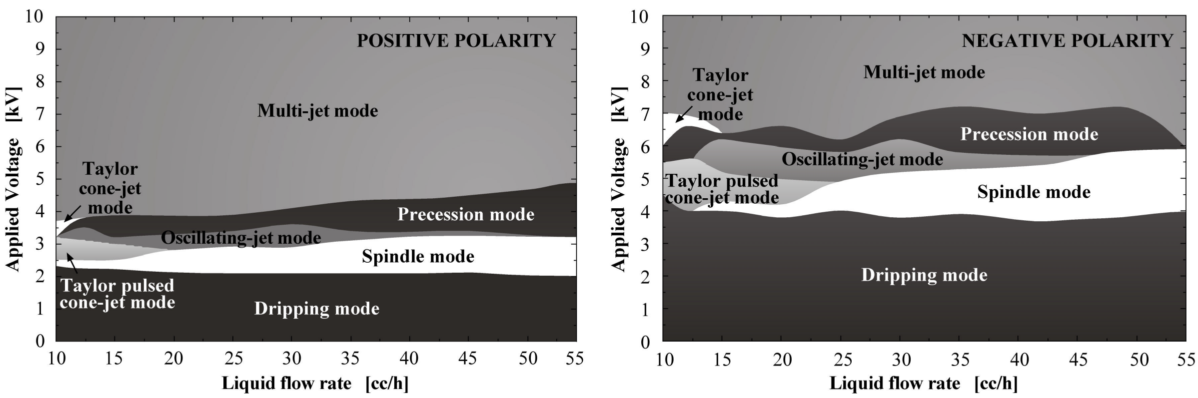

Fig. 8 Map of occurrence of stability regimes for positive and negative polarity.

The two maps do not differ much each other. For both of them the same qualitative description can be given. In the low voltage field, dripping mode is observed for every flow rate. For low flow rate, until 10÷15 cc/h, above dripping mode region, Taylor cone-jet modes, pulsed and then continuous, settle. For higher flow rates stable regimes are, by increasing voltage, spindle, oscillating-jet and precession mode. In the very high voltage field only multi-jet mode can be stabilized.

It should, however, noted that a significant difference exists between the two polarization cases in the voltage values where the different regimes could be observed. In essence the stability map in the negative polarity case appears both to be shifted toward the higher voltage values and the voltage intervals in which the regimes were observed are wider.

In Fig. 9 the profiles of mean drop diameter are reported as a function of the applied voltage at selected values of liquid flow rate, for both polarities. The same consideration made in the presentation of the stability map can be made also regarding these plots: the two pictures do not differ very much in qualitative terms but the profiles are shifted toward the higher voltage range in the case of negative polarity.

In addition, it has to be stressed that in negative polarity higher voltage values could be reached than in positive one before electrostatic discharges arise. As a consequence in negative polarity multi-jet mode is able to produce very small droplets also for high flow rate, as emerges from the observation of Fig. 9. It should also be noted that since electric forces promote liquid breakup mechanisms, and as a consequence droplet size decreases when applied voltage is increased. On the contrary drop sizes increases with flow rates, because of both increased thickness of the jet and reduced effectiveness of electric field, which is masked by the space charge due to greater droplet clouds.

In the low flow rate range mean diameters decrease with applied voltage, while for higher flow rates a maximum in the oscillating-jet mode region can be observed. This effect is only apparent because the data relative to the spindle mode, which is observed at lower applied voltages, are biased by the presence of droplets too large to be collected with the adopted PDA configuration. As a consequence the mean drop diameter computed by the PDA measurements in spindle mode is lower than the real one.

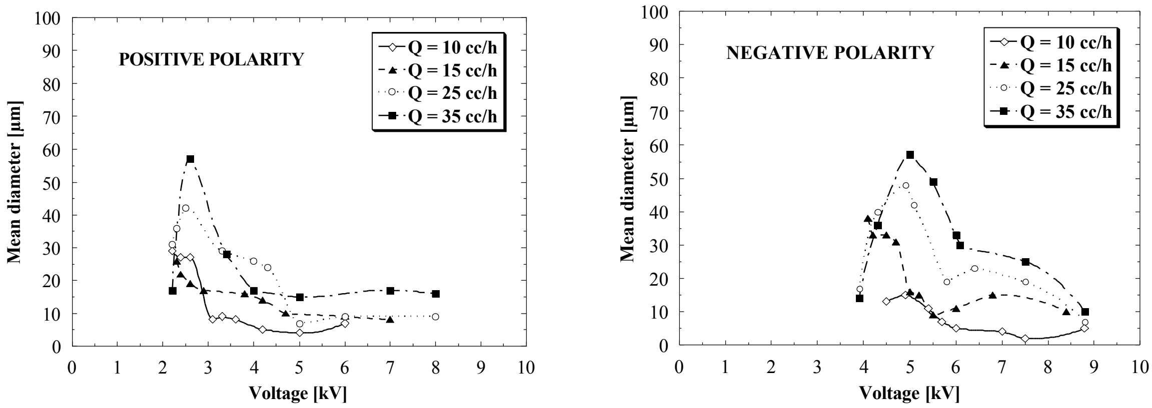

Fig. 9 Mean droplet diameters in positive and negative polarity as a function of applied voltage for different values of liquid flow rate.

4. Discussion

The illustration of the results gave the clear indication that, at least from a qualitative point of view, there is not much difference in the regime occurrence in the two polarizations apart from the voltage shift. So the discussion for the two cases is almost the same but some final considerations that will better clarify possible implications of a polarization change.

Aiming to apply the EHD atomization for practical purposes the atomizing regime characterized by unstable or intermittent operation are of little or no interest. The spindle mode is a typical case of this class of regimes. It is characterized by the coexistence of very large droplets, whose size was estimated from the imaging results to be about 400 μm, and of a finer aerosol (formed by droplets smaller of one order of magnitude), so that just a small portion of liquid flow rate is well atomized. Furthermore, the small and large droplets are not produced in the same time and the size distribution at a fixed section varies in time according to the oscillating behavior of the atomization process. Analogously, the oscillating-jet mode is scarcely interesting because of its widely dispersed size distributions and high mean diameter values. Precession mode, occurring at higher voltage with respect to the previous ones, is characterized by smaller droplets, but still with polidisperse size distributions.

The only two regimes that coniugates the requisites of a good atomization quality and a stable functioning are the Taylor cone-jet mode and the multi-jet mode. In fact, these two regimes

are characterized by a good atomization quality, carrying out very fine sprays, where 90% of droplets are in a diameter range narrower than 6 μm.
A separate discussion has to be made regarding the pulsed Taylor cone-jet mode. It could be considered a suitable condition for practical applications even if it is affected by instabilities that compromise the level of controllability of the process. Data reported in the present paper for pulsed Taylor cone-jet mode agree with the observations by Cloupeau and Prunet-Foch [2]. These authors suggested that jet intermittence compromises the atomization quality and so size distributions present higher mean values and standard deviations than in continuous cone-jet mode. This in contrast with the picture depicted by Grace and Marijnissen [9] that identified the pulsed Taylor cone-jet mode with a special case of the spindle mode. In this hypothesis periodical jet detachment from meniscus would produce larger droplets. The combined use of PDA and visualization diagnostics made in the experimental work here reported can help to clarify the situation. In fact, even though in the adopted PDA configuration very large drops would be undetectable, in this case they would have been visible with the visualization technique (whose lower limit of resolution is in the order of 10 μm). In several run made it was not possible to observe such large droplets in presence of a pulsed Taylor cone-jet regime. A possible explanation of the ambiguity comes from the consideration that the experimental observations reported were all obtained using visualization techniques with poor temporal resolution. In this case the pulsed Taylor cone-jet mode can be hardly distinguished from the stable Taylor cone-jet and many times these two regimes are confused. Analogously, the spindle mode at higher applied voltages generates very small spindles and at a first sight it could be confused with a pulsed cone-jet. The results reported here shows that the pulsed cone-jet differs from the spindle one in that in the first case the size distribution is not bimodal as it is in the second case. This criterion is in principle a very simple discriminator of the two conditions, even if in practice a direct application of PDA technique cannot be used to determine the presence of very large droplets due to its limited dynamic range.
A similar argument can also explain why the region, where the Taylor cone-jet mode appear to be stable (see Fig. 8), seems smaller than that usually reported in literature. This can be partly due to the difficulties in distinguishing between pulsed and steady cone-jet, when pulsation frequency is too high to be caught by optic diagnostics. For instance Noymer [10] used a digital camera acquiring at 30 fps and a shutter time in the order of tenths of milliseconds, which is a time longer than the pulsation period characteristic of pulsed cone-jet. In this case a pulsed jet would appear as a steady one. Nevertheless, it should be mentioned that electrosprays are often operated, in cone-jet mode, with very low flow rate, in the range of 1 or less cc/h, in material deposition processes or in analytical devices (mass spectrometry). In those flow rate conditions the cone-jet should be stable in a wider range of applied voltages due to the lower disturbances induced by fluid dynamic forces (which increase with the liquid flow rate) [11].
Symmetry between polarities is limited to qualitative aspects. All experiments indicate that a direct polarity inversion, being all other parameters kept fixed, change the atomization condition. In general it has been observed that in negative polarity higher voltage *variations* are needed to induce any modifications on spraying conditions. Jaworek and Krupa [12] suggested that leakage of symmetry could be associated to the difference of mass, and then of mobility, between positive and negative charges. An indication of the responsivity of the system to the effects of a change of the electric field can be obtained by evaluating the electrical relaxation time of charges on liquid surface, defined as: $t_e = e/g_l$ (where e is the electrical conductivity of liquid). Spraying modes, giving good atomization quality, can be observed only when t_e becomes shorter than the other characteristic times of the EHD

atomization process. A short relaxation time means that spray system reacts faster to electric field variations. In negative polarity t_e should be longer than in positive. That would reduce the sensitivity of the spray to electric field variations, including those induced by the onset of electrostatic discharges. In negative polarity, indeed, spray appears to be less disturbed by these discharges, so that multi-jet mode can obtain better performances, in terms of droplet size, than in positive polarity.

5. Conclusions

As maps of occurrence show, negative polarity, in the used experimental configuration, corresponds to wider stability regions for every spraying mode. Consequently, negative polarity can give better performance in terms of both quality and stability of the atomization. In the low flow rate field Taylor cone-jet mode, operated in negative polarity, could result useful for deposition applications. However combustion applications require higher flow rates. In this range multi-jet mode appears to be a good solution: especially in negative polarity, it produces a very fine spray, droplets being smaller than 10 μm. Studies in combustion conditions have still to be done in order to verify whether negative polarity could be beneficial to the global combustion process being less sensitive to the presence of the flame of the positive polarity.

6. References

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