ATOMIZATION AND COMBUSTION OF A SIMPLE ELETTROSPRAY

A. Cavaliere*, R. Ragucci, F: Beretta** and C. Allouis****
email ragucci@irc.na.cnr.it
*** Dip. Di Ingegneria Chimica – Universita`Federico II**
**** Istituto di Ricerche sulla Combustione – C.N.R.**
P. Tecchio, 80 - 80125 – Napoli – Italy

Abstract

A simple atomizing device is presented capable of generating controlled spray by using an electric field either in isothermal and burning conditions. The stability operating range of controlling parameters (e.g. liquid flow rate and applied voltage) is determined. The coupling of atomization and combustion processes is analyzed by measuring, using a PDA system, the drop diameter distribution as well as the radial and axial components of drop velocities. Preliminarily the influence of controlling parameters on the droplet size is presented and discussed.

The spray structure as well as its evolution in space and time is presented in selected conditions, chosen on the ground of the preliminary analysis. The presence of the flame affects significantly the spray shape and the droplet dimensions. This effect is particularly relevant in the higher liquid flow rate case. A deeper analysis of the measurements allow for the determination of relative importance of different physical effects in the different conditions. The final conclusions of the paper is that the coupling between atomization and combustion processes can be hardly forecasted without a thorough analysis of the spray characteristics in the specific working condition. This poses a severe challenge for the practical application of these atomizing system for the set-up of effective combustion controlling systems that want take advantage of electric field modulation.

Introduction

Atomization of liquid fuels by means of electro-hydro-dynamically assisted nozzles could represent a very interesting technique to increase the performance of combustion systems. In fact, the fast time response typical of electrical system and the residual electrical charge deposited on the droplets could allow for an effective control of atomization and drop dispersion processes. The potential range of application of such techniques is very wide and span from simple deposition system, used in material synthesis, to internal combustion engines used in power generation system.

A large number of paper has been published in recent years on the atomization peculiarities of electro-hydro-dynamically aided systems and the behavior of charged droplets subject to thermal field has been investigated either theoretically or experimentally. On the other hand, the effect of the mutual interaction of combustion and atomization processes has not yet been clarified. Nevertheless, this interaction represents a key point in the assessment of realistic potentialities of electro-hydro-dynamical systems exploitation in combustion systems.

The nature of this interaction is intrinsically complex and a thorough description of even its phenomenology is difficult. As matter of fact, the pool of radicals formed during the chemical reactions taking place in the flame regions interacts with the charged droplet in a complicated way and can affect the droplet cloud shape and behavior. On the other hand the electric field itself interacts with the flame and, as a consequence, it can be expected that the flame be influenced by the electric field presence.

It can be envisaged that atomization and combustion processes cannot be decoupled and their characterization has to be attempted using a systematic approach. In this paper a systematic characterization of well-defined nozzle configurations operated in the same feeding and applied voltage conditions is presented. This paper aims both to identify the ranges of fuel flow rate and of applied voltage in which a stable combustion condition can be established and to determine the changes in the spray droplets size and velocities induced by the combustion process.

Experimental Set-up

The atomizer used to this aim is a simple coaxial system, sketched in Fig. 1, in which a stainless steel needle is used to fed the liquid fuel (a mixture of n-heptane and an antistatic additive). During the experimental work different needles with and inner diameter from 0,1 to 0,8 mm have been tested. The needle is hold by a PTFE insulator in the center of a stainless pipe with a 5 mm inner diameter. Around the pipe a large annular duct allows the supplying of an air stream. In the annular duct a bed of spherical glass particles llow for the

straightening of an air flow used to prevent the accumulation of liquid and to shield the spray from external perturbations. On the glass balls bed a metallic mesh electrically connected to the external pipe and to the atomizer body acts as the cathode of the electrical system.

The external air flow velocity has been kept constant and very low (with respect to the droplet velocities) in all the investigated conditions in order to avoid a significant interaction with the atomization and combustion processes.

The liquid fuel was supplied to the needle by means of a peristaltic pump operating in the range from 10 up to some hundreds of cc/hr. A dumping tank and a capillary pipe were inserted in the feeding line in order to smooth away possible oscillations induced by the pump in the fuel flow rate when small amount of liquid were supplied.

A purposely realized voltage generator capable of supplying voltages up to 10 KV was used to generate the electric field, In a great part of the tests a positive voltage was applied to the needle while the remaining part of the atomizer was kept at ground level. In this way an intense electric field in the spatial region between the needle and the pipe was generated. Some tests were also conducted inverting the polarization of the electrodes in order to evidence possible effects on the atomization and combustion processes.

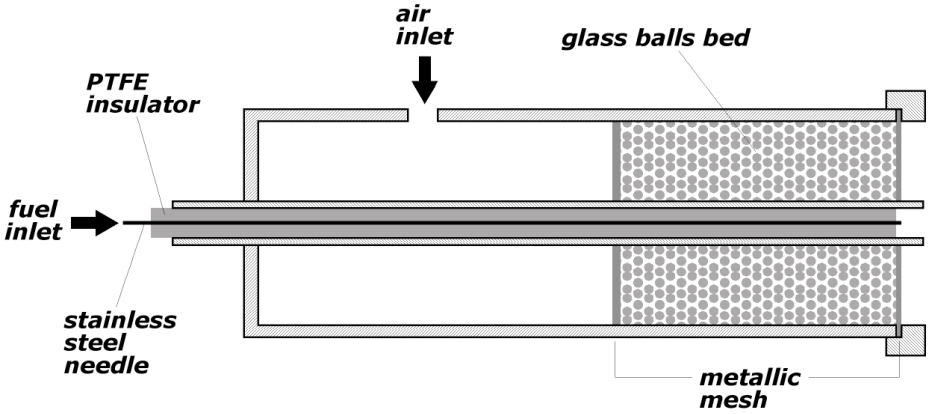

Figure 1. Schematic of the atomizer.

Droplet size distribution as well as axial and radial velocities has been measured by means of a PDA system both along the spray axis and in the radial direction at selected distances from the nozzle. As a complementary technique an high resolution CCD camera with pulsed laser illumination has been used to visualize the instantaneous distribution of droplets in the different conditions.

Results and Discussion

Flame stability

A relevant part of the work aimed to the determination of the burner geometric configuration that could assure a satisfying functioning of system in terms of flame stability. A preliminary work made in isothermal conditions indicated that a reasonable performance of the system, in terms of atomization quality, could be achieved by using a needle with an outside diameter of 0.46 mm and an inside diameter of 0.25 mm.

The needle inner diameter is 254 µm and the outer diameter is 457 µm.

It was then decided to use this needle in the characterization of flame stability. To this aim the distances between the needle and the top of the co-annular electrode were changed in a systematic way and the interval of stable combustion were observed. It was thus individuated a suitable geometric configuration to be used for the subsequent characterization of the spray atomization and combustion.

In Fig. 2 is reported the domain of stable combustion, in terms of liquid flow rate and applied voltage, as it was observed for the above mentioned configuration. It was obtained by fixing the liquid flow rate and increasing the voltage in 100 Volt steps. At each working point the flame was observed and images of the flame were taken for a time long enough to allow for the stabilization of the flame. The shadowed line corresponds to the region in which the flame appeared to be stable (e.g. it remains substantially invariable without significant pulsation). The dotted line marking the upper limit of stable combustion region indicates the maximum voltage applicable at each liquid rate before the occurrence of an electrical discharge between the needle and the annular electrode. The continuous line marks the lower limit of applied voltage under which the flame became unstable and extinguishes due to the very poor atomization quality. It is noteworthy that it was not possible to find a real

upper limit for the liquid flow rate in which the flame could be stabilized. Nevertheless at very high fuel flow rates the liquid jet was clearly visible very far from the needle and the flame was stabilized around the liquid jet.

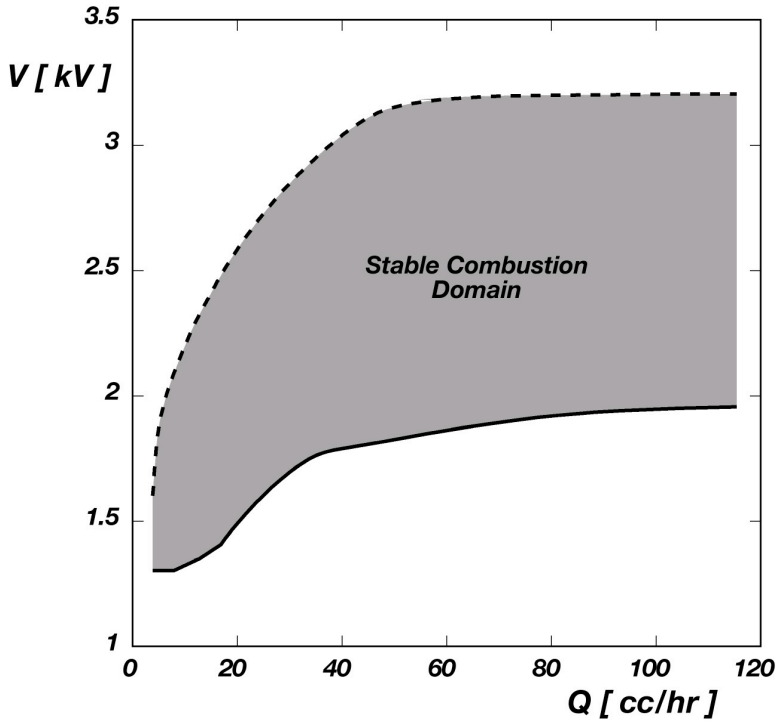

Figure 2 Domain of stability for the spray in Combustion.

An explanation of the observed stability domain can be found in the droplet size profiles measured at 2 mm of distance from the nozzle at different applied voltage as a function of the liquid flow rate reported in Fig. 3.

As shown in figure, the droplet diameter decreases with increasing voltage from 1.7 up to 2.5 KV due to the reduction of Taylor's cone apex angle at increasing voltage. Vice versa with increasing the flow rate an increase of final droplets diameter is observed due to the increase of this angle.

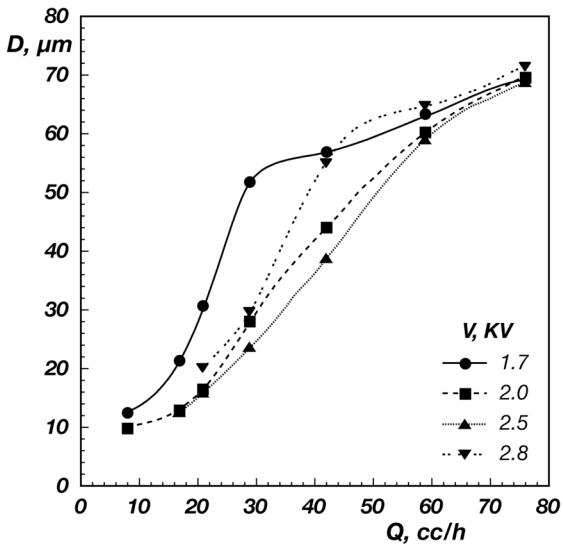

Figure 3 Values of the mean diameter of droplets spray vs fuel flow rate.

In view of these results it can be inferred that the increase in minimum voltage required to stabilize the flame observed at increasing the liquid flow rate (see solid line in Fig. 2) is due to the degradation of atomization quality with production of larger droplets.

From Fig.3 it can also be observed that a further increase in the applied voltage above 2.5 KV causes a significant increase of droplet size. This can be another explanation of the impossibility of stabilizing a flame at very high voltage. Finally, from Fig. 3 it can be observed that the size of the droplets does not depend on the applied voltage at high fuel rates. This is a fairly good explanation of the essential independence of the stability domain on applied voltage at high fuel flow rates (see Fig. 2).

Atomization-combustion interaction

As reported in the introduction section the coupling of atomization and combustion processes is complex due to the multiple mutual effects acting simultaneously. An attempt to give at least a phenomenological description of such interaction the two conditions summarized in Table 1 were chosen. The first condition (named A) correspond to a fuel flow rate of 17 cc/hr and an applied voltage of 1.7 KV. The second one (B) corresponds to 34 cc/hr and 2.5 KV. The two conditions have a very different atomization quality (see Fig. 3).

Case	***Fuel flow rate***	***Voltage***	***air flow***
A	*17 cc/h*	*1.7 kvolt*	*1000 nl/h*
B	*34 cc/h*	*2.5 kvolt*	*1000 nl/h*

Table 1

In the two selected cases drop size distribution along with axial and radial velocity components were characterized in detail both in isothermal and burning condition. The measurements were made along the axis of the nozzle and along selected radii.

The mean diameter axial profiles in the two conditions are reported in Fig. 4 for both isothermal and burning cases. Measurements was concentrated in the first region of the flame from 2 mm above the nozzle (which was the minimum distance at which the measurement was possible) up to 6 mm above the nozzle, which was situated at the base of the luminosity emitting flame region.

In isothermal conditions the difference in the droplet sizes of the two considered cases is not very significant and also the difference in their axial evolution is not relevant.

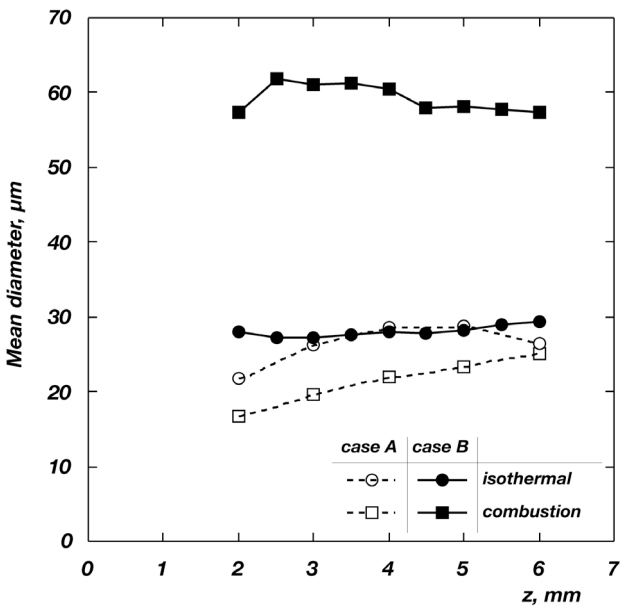

Figure 4 Values of mean dimensions of droplets for conditions "A" and "B" in isothermal and combustion regimes.

In presence of the flame for the condition A it can be observed a general decrease of droplet size with respect to the isothermal case. The axial profile of the droplet size in burning condition shows an increase of droplets dimensions. On the opposite, in case B, even if the diameter values in isothermal condition were not

very different with respect to the first case, it is possible to observe a strong increase of the droplet sizes passing from isothermal to combustion condition.

As matter of fact, the histograms relative to the case A reveal a standard behaviour of a spray subject to evaporative effects. In particular at 2 mm above the nozzle the narrow distribution of diameters around the average value give rise to the appearance of smaller droplets as a consequence of the evaporation progress. At higher distances from the nozzle the broader diameter distribution generates a general shift of the histogram toward smaller droplet diameter values.

The same considerations cannot be applied to the case B. In fact, in this case the evaporation effects, even if a selective evaporation is invoked, could not give rise in presence of the flame to classes of droplets of greater dimension than in the isothermal case. Another possible explanation of the observed increase of the average droplet diameter could be the selective drifting of smaller droplets toward the spray periphery, due to the combined effect of charge repulsion and electric field action, that was observed in cold conditions and can explain the convexity of the profile in isothermal condition in case A.

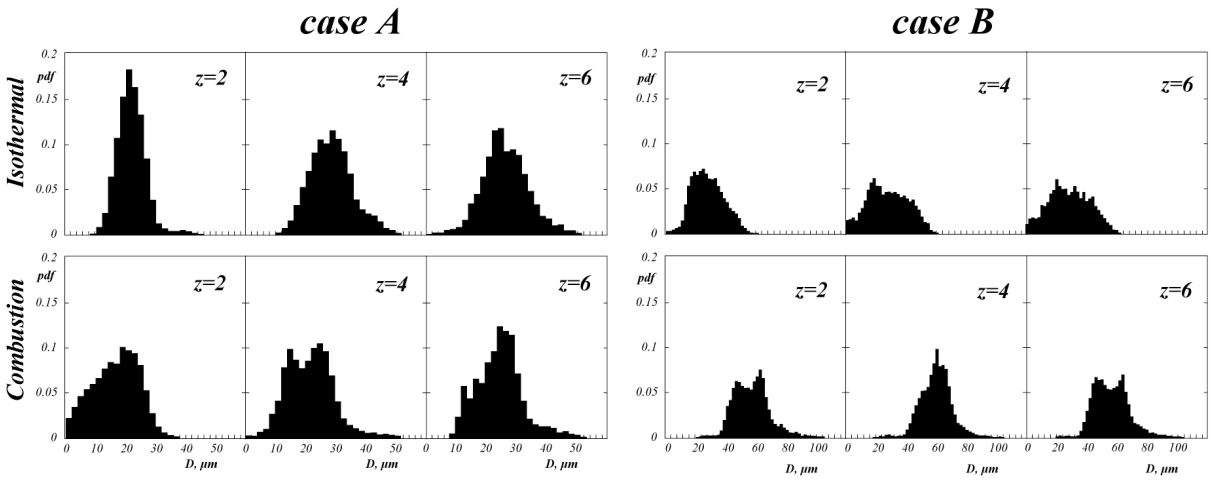

Figure 5 Histograms of the droplet diameters at selected positions on the spray axis for cases A and B both in isothermal and burning condition.

A clarification of this point comes from the analysis of the histograms of the velocities reported in figure 6. In this figure the axial and radial components of the velocity measured along the axis of the spray are reported for the two cases considered and both in isothermal and combustion condition. The histograms of the axial velocity component of the droplets show that passing from isothermal to combustion condition the velocities are less dispersed and there is a clear acceleration of the droplets due to the flame buoyancy.

The radial velocity component histograms reveal a relative broad dispersion of velocities in isothermal conditions. This causes the opening of the spray to form a cone shaped cloud of droplets. A closer analysis of the velocities of different classes of droplet sizes (not reported here) shows that the smaller droplets are shifted away from the centre of the spray probably due to the repulsion forces acting on the charged drops. In burning conditions the radial velocities vanishes in both case A and case B. In this condition the spray is essentially a stream of droplets as it has been confirmed also from the observation made by using the high resolution CCD camera with pulsed laser illumination. As a consequence a selective spatial displacement of the droplets cannot be invoked to explain the huge increase in the mean size observed in case B.

From a speculative point of view it could be suggested that the explanation of this increase relies in a change of the atomization regime induced by the presence of the flame. In fact, the applied voltage (2.5 KV) is close to the upper limit of stability for the flame at the 34 cc/hr fuel flow rate (see figure 3). In these conditions it is likely that the Taylor cone formed at the top of the needle is less stable than in isothermal case [4,5]. The double effect of the radiative heating from the flame and the modification in the electric field induced by the free charges present in the flame can lead to the destabilization of the cone and to a sensible decrease in the atomization quality. This effect is not dissimilar from the one observed at very high applied voltages (curve at 2.8 KV in figure 3) where the increased voltage disrupt the cone stability and produce an unstable atomization regime (either a multi-jet or a whipped regime) characterized by larger droplet sizes[5].

Conclusions

A thorough characterization of two significant conditions of an electro-hydro-dynamically assisted spray showed that the presence of a flame greatly influences the atomisation process. In fact, while the spray has a

cone shape in isothermal condition, passing to combustion condition it can observed, in correspondence of the same liquid flow rate and applied voltage, that the spray is confined on the axis due both to the buoyancy forces and the reduced effectiveness of electric field.

The droplet size behavior passing from isothermal to burning conditions is different in the two cases. In the first case (named A in the paper) the evaporation seems to be the cause of the observed differences. In the second case (B) the change cannot be explained by invoking any peculiar evaporation effects. In this case the interaction between the flame and the electric field could induce a strong change in the atomization regime with a consequent degradation of atomization quality.

These observations pose an important challenge for the potential application of the electro-hydro-dynamically assisted spray in practical combustion systems. In fact, the capability of effectively controlling a combustion process by controlling the spray by electrical modulation has to be reconsidered taking into account the coupling of atomization and combustion processes.

References

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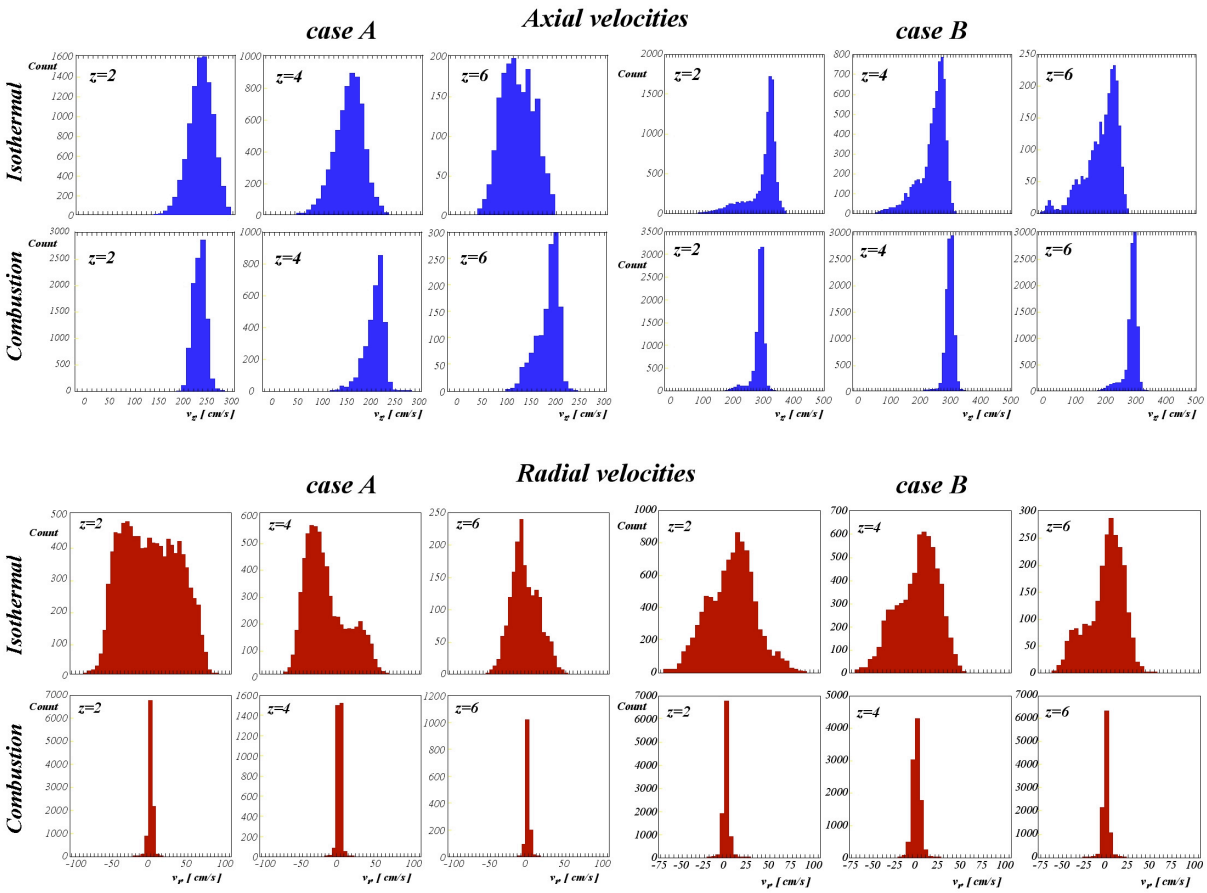

Figure 6 Histograms of the axial and radial components of droplet velocities at selected positions on the spray axis for cases A and B both in isothermal and burning condition.