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# PHENOMENA ASSOCIATED WITH COMBUSTION OF ELECTROSTATICALLY CHARGED DROPS

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**ABSTRACT**

The use of an electric charge to facilitate the dispersion of a liquid inside a gaseous fluid (electrospray) is an used practice in different fields [1] (mass spectrometry, spray painting, pesticide dispersion, drug delivery through aerosol), and potentially very interesting for the spray combustion. Many are the works in the literature, dealing with the effect of an electric field, applied in different manners, on combustion. However, at the best of our knowledge, there are no detailed studies about phenomena taking place when a single fuel droplet burns after being electrically excited through electric induction. The objective of this work is to investigate these phenomena through high-speed imaging technique, in order to provide a better understanding, at least qualitative, to the combustion analysis of a spray of electrically charged droplets. It will be shown that a precise and repetitive sequence of phenomena takes place when an isooctane droplet burns after an electric potential is applied. In particular it will be shown that the secondary atomization process occurs even in a combustion environment. Moreover, a quantitative analysis of the influence of the electric field on the morphology of the reaction zone has been performed, showing that appropriate configuration of the ground electrode can be useful to enhance fuel air mixing.

## INTRODUCTION

The use of an electric charge to facilitate the dispersion of a liquid inside a gaseous fluid (electrospray) is an used practice in different fields [1] (mass spectrometry, spray painting, pesticide dispersion, drug delivery through aerosol), and potentially very interesting for the spray combustion.

The first requirement, essential for a good combustion, is in fact an intimate mixing between fuel and combustive; this condition allows to obtain a good combustion efficiency with a very low formation of pollutants. The atomization through electrostatic charge decouples, contrarily to what happens with the traditional injectors, the droplets dispersion from the injection velocity, so introducing one more degree of freedom in spray control.

Many are the works in the literature, concerning the effect of an electric field applied in different manners, on combustion: in [2], Gomez and Chen have experimentally pointed out for the first time the possibility to obtain a secondary atomization for an heptane electrospray even in a combustion environment. Fundamental for this phenomenon to appear is a sufficient drop evaporation before entering in he reaction zone: in this zone the consistent presence of ions neutralizes the electric charge on the drop.

In [3], the possibility of reducing soot emissions of propane combustion by means of corona discharge in the proximity of the reaction zone has been evaluated. The hypothesis investigated by the authors is that electrons carried by electric wind are capable of influencing the kinetic mechanism of soot formation.

In [4], Yuan et al. visually investigated the effect of electric fields on diffusive ethylene flames, concluding that there is an influence of the electric field on the reaction zone.

In [5], the Authors have developed an analysis of the effects of the electric field on the combustion of an octane pair of droplets having an original diameter of 0,70 mm; they showed that there is a critical distance over which the reaction zone of the two droplets are separated.

*Marcum e Ganguly* [6] have investigated the application of a direct and alternating electric field in the reaction zone of air-propane premixed flames, showing that the turbulence introduced by the presence of this electric field leads to an increase of reaction rate.

*Kyritsis et al.* [7,8] have optimized the efficiency of a small burner with electrospray for thermal power generation (about 100W).

None of the cited papers dealt in detail with phenomena taking place when a single fuel droplet burns after being electrically excited through electric induction. The objective of the work is to investigate these phenomena through high-speed imaging technique, in order to provide a better understanding, at least qualitative, to the analysis on the combustion of a spray of charged droplets.

## EXPERIMENTAL SETUP

A small quantity of isooctane (around $10^{-2}$ ml) dripped from the tip of a capillary, is measured using a syringe pump. The capillary is charged, by means of a high voltage generator, to several kV with respect to the ground, represented by a metallic plate, placed at a distance of 35 mm. The drop is ignited by means of an electric arc obtained by a second high voltage generator between two tip electrodes. Combustion is observed with a high-speed camera Kodak Super 10K (500 frames per second, resolution 512x240 pixel, exposure time 1/20000s).

In order to synchronize the syringe pump, the electric arc and the camera, a photodiode and a laser have been aligned with the tip of the capillary. Accumulating around the tip of the capillary, the drop shades the light of the laser directed on the photodiode, whose electric signal is used to trigger either the start of the image acquisition through the high-speed

camera, and the release of the discharge used to ignite the drop. A scheme of the experimental setup used is shown in Fig. 1. (In Fig. 1 cables, syringe pump and high voltage generator are not shown).

It could be observed that the drop dimension, necessary to obscure laser light enough to trigger the system, depends on the particular alignment between laser, photodiode and capillary. Because of this, only comparison between movies taken with the same alignment will be shown. The only parameters varied in the repetitions shown here after is the voltage applied.

Moreover, in order to let the system work properly, the electrospray must be operated in the "dripping mode": this is the only functioning mode which permits sufficient liquid accumulation at the tip of capillary to shade laser light. The maximum voltage applied musts then be lower than the transition value to the cone-jet mode. In our experimental conditions it has been found that the threshold value is somewhat bigger than 3 kV. We assumed a voltage of 3 kV as the maximum applied voltage.

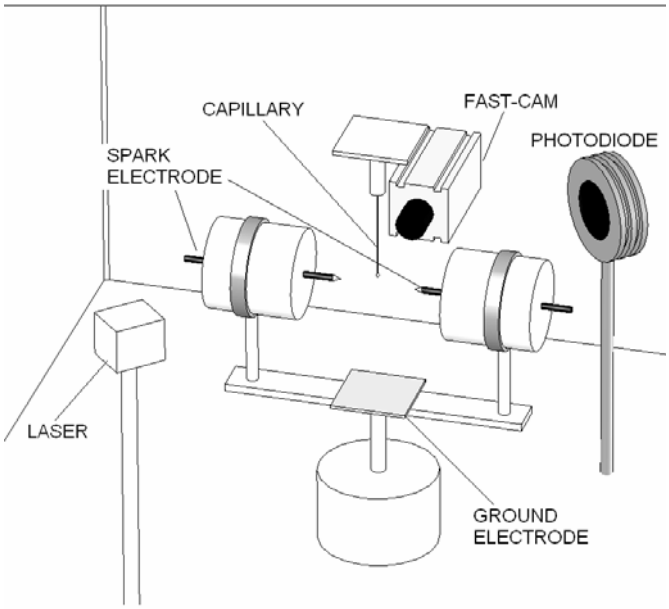


**Fig. 1: Experimental setup scheme**

## DESCRIPTION OF THE PHENOMENA

A voltage in the range of 0-3 kV with a step of 1 kV has been applied between the capillary and the ground electrode and, for each voltage value, the acquisition has been repeated several times. As well known in literature, electric field calculation for electrospray is not a trivial task. A first rough estimate of the electric field can be obtained dividing applied voltage by the distance measured between electrodes: for a voltage in the range 1-3 kV this results in an electric field in the range of 28-85 kV/m.

For each applied voltage, it was possible to identify a precise and repetitive series of phenomena. Without an applied voltage it can be observed that, few hundredth of second after the spark, the drop separates from the capillary that burns falling down; a laminar flame then appears, burning the remaining fuel around the tip of the capillary.

When the applied voltage increases up to 1 kV, the separation of the drop can be still observed; the drop burns while falling (this phenomenon has been observed for all the values of the voltage applied to the capillary, and can be explained taking into account that the first liquid drop at the tip of the capillary can discharge through the corona discharge, therefore not experiencing the applied voltage). In the following, it is possible to observe that the flame develops in a laminar way for about 0,26 s. Around this moment it can be observed, in the different repetitions, that a liquid jet of secondary droplets from the "mother" droplet at the capillary tip [Fig. 2] is emitted. In the following frames, no combustion phenomena can be observed, related to the combustion of these secondary droplets.

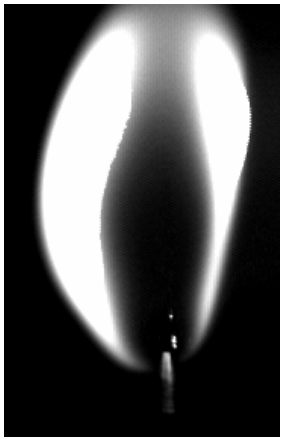

**Fig. 2: V = 1 kV, secondary atomization**

In [Fig. 3], the isooctane droplet with the reaction zone in condition of laminar flame is shown for several values of applied voltage (white spots are originated by the laser which remains pointed on the drop for the whole length of the experiment). It can be immediately observed that the dimension of the reaction zone in the dominant direction of the electric field decreases with increasing the applied voltage. A more quantitative measurement of such influence is reported in the next paragraph.

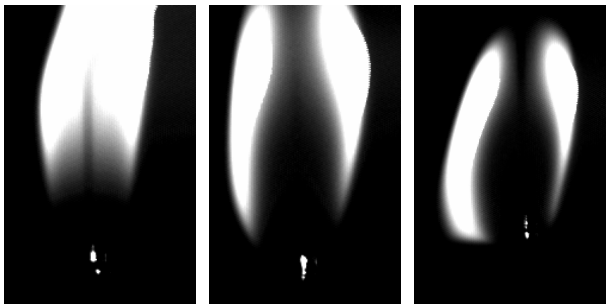

**Fig. 3: reaction zone for V = 1 kV, V = 2 kV, V = 3 kV**

Increasing the voltage to 2 kV, the observed phenomenon is substantially the same until the mother drop breaks up. In the picture [Fig. 4] showing the emission of the secondary jet, it can be observed that the secondary spray angle is greater than in the case of V = 1 kV. Moreover, two frames later a secondary reaction zone can be observed. The presence of this reaction zone can only be explained by taking into account the combustion of the liquid emitted in the secondary jet. It is interesting to observe that the secondary jet direction is coincident with the main direction of the electric field.

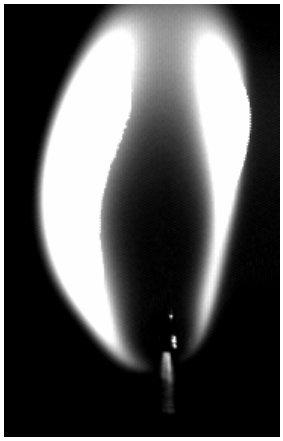

**Fig. 4: V = 2 kV, secondary atomization**

When the voltage applied reaches the value of 3 kV, the phenomenon becomes too fast to be observed. The only thing we were able to see is a sudden increase in dimension and brightness of the reaction zone [Fig. 5]. The increase in brightness saturates the CCD. The laminar combustion phase duration is substantially shorter with respect to the case V = 1 kV (0,18 s vs. 0,26 s).

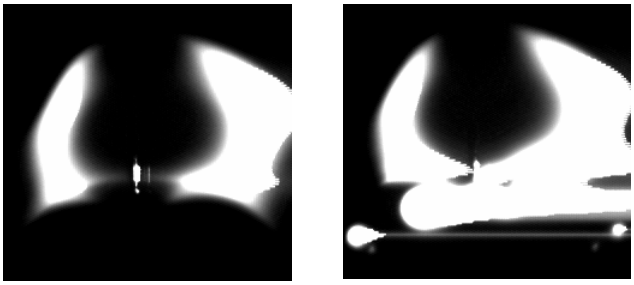

**Fig. 5: V = 3 kV, secondary atomization**

Another difference can be found observing frames immediately after isooctane ignition [Fig. 6] for the case V = 0 kV and V = 3 kV. Combustion starts more rapidly with increasing the applied voltage, and droplets are emitted in all directions immediately after ignition.

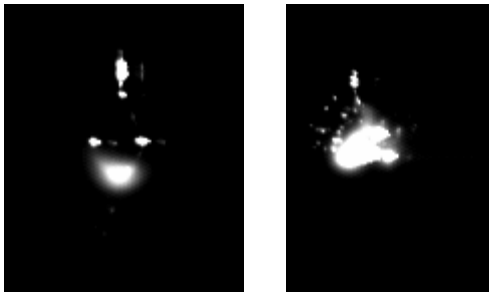

**Fig. 6: droplet ignition. V = 0 kV, V = 3 kV**

The comparison between the same phenomenon observed at different voltage values suggests some consideration. First of all, there is secondary atomization even in a combustion environment. This happens when the drop dimension has been reduced enough to reach the Rayleigh limit. Unfortunately it is not possible to have a measurement of the droplet dimension at the moment of the secondary atomization with the technique used in this work. Increasing the applied voltage, the Rayleigh limit is reached more rapidly. This confirms the proportionality of the charge to mass ratio to the applied voltage.

It is well known that the liquid must evaporate before burning, and that the rate of evaporation is inversely proportional to drop radius. This means that, from images shown, the voltage applied has an influence on the electrostatic pressure that causes the secondary jet to be emitted, and therefore on the secondary droplet radius. In fact, there is no combustion of the secondary jet for the case V = 1 kV, there is combustion after a few milliseconds for the case V = 2 kV, there is "immediate" combustion (i.e. liquid jet evaporation is not observable in our films) for the case V = 3 kV.

We mentioned before that electric field induces modifications in the reaction zone. In order to have a first estimate of such influence, the height of the reaction zone was measured in laminar conditions. In fact, this is the flame dimension in the main direction of the electric field.

In order to measure flame height an apposite Labview® VI has been implemented. The VI reads a series of frames, and applies a "threshold algorithm" on each of them [Fig. 7]. The algorithm compares the brightness value of each pixel with a threshold value of 250. If the value is greater than the threshold, the pixel is set to 255, otherwise it is set to 0. An image with only two brightness values (0 and 255) is obtained in this way. On this image, Labview subroutines for flame measurements can be applied, and the change with the time of the height of the reaction zone can be obtained.

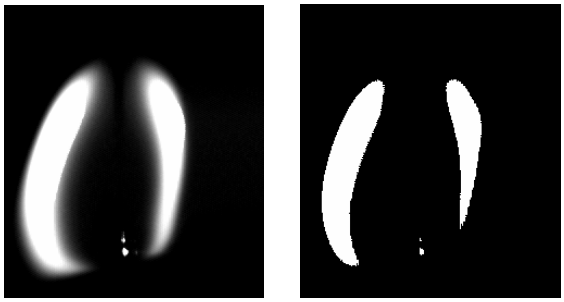

**Fig. 7: effect of the threshold algorithm**

Obviously, all the images compared in this way have been acquired with the same camera parameters, and the same camera alignment. These are necessary conditions for pixel measurements comparison. Moreover, such measurements have been performed only on laminar flame frames. In fact in this phase the phenomenon is stable and regular, and measuring reaction zone makes sense.

In [Fig. 8], measurements of reaction zone height for several voltage values is shown. Measurements for each repetition start at the first frame where a laminar stabilization of the flame is observed, and are referred to the laminar flame period: therefore measurement duration decreases with the applied voltage increasing.

Observing Fig. 8, it can be observed that all repetitions start with the same value: this happens because reaction zone initially extends beyond the camera observation zone. Reaction zone height decreases with time, for all repetitions and for all values of the voltage applied: however the rate of reduction and the final value are not the same. The arrow indicates voltage increase. For the case V = 1 kV, the reaction zone saturates camera observation zone for about 0,15s. This time decreases when the voltage applied is increased till 3 kV.

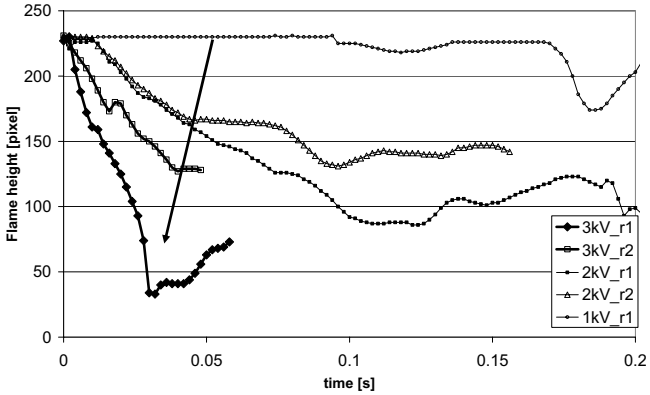


**Fig. 8: height of the reaction zone**

Actually the choice of the first frame for this analysis has been made from visual observation of images sequence. We tried to adopt a uniform criterion to determine when the flame had to be considered stable. An error in choosing the initial frame for the analysis does not change the observed phenomenon. However, we used another parameter which is not influenced on this choice.

In Fig. 9 the derivatives with respect to time of the Fig. 8 curves are shown (the arrow indicates voltage increase). The first measurement for the case V = 3 kV has been excluded because of its irregularity. It can be observed that the two repetitions for the case V = 2 kV have similar slopes, and minor (in absolute value) of the case V = 3 kV. Images shown clearly demonstrate that the shape of the reaction zone is influenced by the presence of the electric field.

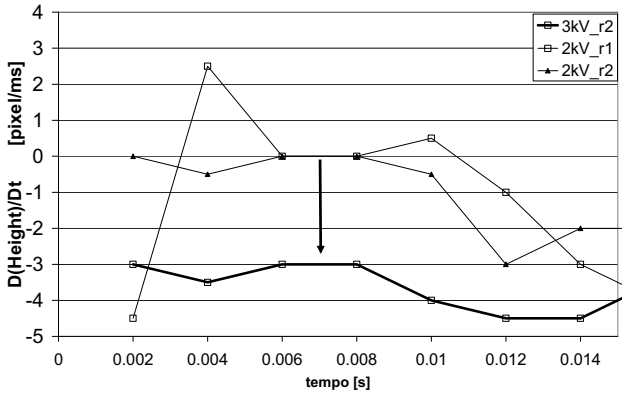


**Fig. 9: Derivatives of the curves shown in Fig. 8**

In particular it can be hypothesized that the reaction zone assumes an equilibrium configuration between the buoyancy forces, which push the reaction zone up, and the electric field action. In the adopted configuration of the electrodes, the positive electrode (capillary) is about at the same height of the reaction zone. The ground electrode is under the reaction zone, therefore it seems like if the reaction zone is "attracted" by the ground electrode.

If a confirm of this finding will be obtained by experiments with different electrode configurations, the use of the electric field to extend the reaction zone could be adopted. First experiment in this direction will be the execution of tests similar to the presented ones but with the ground electrode higher than the capillary. In this way the action of the electric field and of the buoyancy forces will be synergic.

Increasing the volume interested by combustion reactions is very interesting both for combustion efficiency and pollutant emissions formation. In fact it can be stated that "most of soot formation process takes place in the main reaction zone, where there is a conflict between oxidation and hydrocarbon concentration greater than the critical" [9]. To be successful in expanding the main flame reaction zone will permit to maintain the hydrocarbon to oxygen ratio below the critical one for soot formation.

## CONCLUSIONS

It has been clearly shown that electric charge in a liquid fuel affects the mixing with the combustive. This effect can be addressed to a secondary atomization mechanism: the liquid drop at the tip of the capillary is, obviously, not directly interested by a combustion phenomenon; it is interested only by evaporation and experimental results [10] show that, during evaporation of a liquid electrically charged, the charge remains trapped inside the liquid phase, and so the charge/mass ratio increases until it eventually reaches the Rayleigh limit, leading the mother drop to break and to secondary droplets detachment. If these droplets have a sufficiently small diameter, they burn quite instantaneously compared to the characteristic combustion time of the mother drop.

Increasing the voltage applied to the capillary (and therefore the charge on the drop), the Rayleigh limit is reached in a shorter time, causing a bigger dispersion (opening of the spray cone in 1kV and 2kV cases), and, acceptably, a smaller dimension of secondary droplets. In fact the secondary droplets do not burn applying 1 kV voltage, they burn after they left the main reaction zone with 2 kV voltage, burn sensibly before they left the reaction zone with 3 kV voltage. The decrease of the time interval required for the evaporation, clearly indicates a decrease of the droplet radius.

Moreover, the influence of the application of an electric field on the reaction zone configuration was analyzed. We hypothesized that the reaction zone shape is the result of an equilibrium between buoyancy forces and electric field forces. This phenomenon, if exploited with a suitable electrode configuration, can increase the flame zone volume, therefore improving air-fuel mixing and decreasing hydrocarbon to oxygen ratio in the whole reaction area.

## NOMENCLATURE

| Symbol | Quantity | SI Unit |
|---|---|---|
| V | Applied Voltage | Volts |

## REFERENCES

1. A. Gomez, The Electrospray: Fundamentals and Applications, *Proceedings of the 3rd World Conference on Experimental Heat Transfer, Fluid Mechanics and Thermodynamics*, Elsevier, 1993.
2. A. Gomez, G. Chen, Charge induced Secondary atomization in Diffusion Flames of Electrostatic Sprays, *Comb. Sci. and Tech.*, vol.96, pp 47-59, 1994
3. H. Ohisa, I. Kimura, H. Horisawa, Control of Soot emission of a turbulent diffusion flame by DC or AC

Corona Discharges, *Comb. and Flame* 116, pp 653-661, 1999.

4. Z. Yuan, U. Hedge, G.M. Faeth, Effects of Electric Fields on Non-Buoyant Spherical Diffusion Flames, Brief Communication on *Comb. and Flame* vol. 124 pp. 712-716, 2001.
5. K.Okai, T.Ueda, O.Imamura, M.Tsue, M.Kono, J.Sato, D.L.Dietrich, F.A. Williams, Effects of DC electric fields on combustion of octane droplet pairs in microgravity, *Comb. and flame* vol.136, pp390-393, 2004.
6. S.D. Marcum, B.N. Ganguly, Electric-Field-induced flame speed modification, *Comb. and Flame* vol.143 27-36, 2005
7. S. Kaiser, D.C. Kyritsis, P. Dobrowolski, M.B. Long, A.Gomez, The electrospray and combustion at the mesoscale, Special Issue of the "*Journal of Mass spectrometry society of Japan*" in honor of John B. Fenn.
8. D.C. Kyritsis, B. Coriton, F. Faure, S. Roychoudhury, A. Gomez, Optimization of a catalytic combustor using electrosprayed liquid hydrocarbons for mesoscale power generation, *Comb.and flame* vol.139, pp.77-89, 2004.
9. Z.A. Mansurov, Soot Formation in Combustion Processes (Review), *Combustion, Explosion and Shock Waves*, Vol.41, no 6, pp 727-744.
10. A.G. Bailey, Electrostatic Spraying of Liquids, University of Southampton, UK 1988