Control of the Dripping Phenomena by electric fields

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Abstract— **We analyze in this article the alteration of the dripping phenomena under a periodic regime of detaching droplets that are electrified by induction. The condition imposed in the hydraulic system and that enables the droplet formation is a constant height of liquid column. Under this condition, the electrification of the droplets has consequences in the flow rate and on the dripping period. We propose to analyze the link between these two magnitudes and as a consequence of electrification is observed for a given height of liquid column a decrease in flow rate and in droplet volume accompanied by an increase in dripping period**

I. Introduction

Because of its potential in producing smaller drops than the capillary radius, the formation of charged drops in an electric field has been studied in big detail by numerous researchers.

Some of these efforts have been mainly directed towards the computational analysis of the equilibrium shapes and the stability of pendant drops in an electric field or in a characterization of the atomization produced by electrohydrodynamic jetting. (Clopeau & Prunet Foch1990)

By contrast, there has been much less studies of the effects of an electric field on the drop during its formation from a nozzle via the dripping mode at low flow rates.

Most of the previous theoretical and experimental works have aimed at predicting certain gross features concerning the sizes and amount of charge carried by the drops as they break off the nozzle as functions of the strength and orientation of the electric field, fluid properties and nozzle types. More recent studies have analyzed the evolution in time of the shape of the forming drop and the rupture of the interface of the growing drop to form discrete drops (Zhang & Basaran 1996).

In this work we concentrate our analysis on the characteristics of the phenomena of periodic dripping regimes when a meniscus is electrically stressed by induction and the flow is produced from a constant level reservoir.

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The objective of this work is to analyze the changes produced on the dripping frequency and on the flow rate by the electric field action when flow occurs as a consequence of keeping constant the height of liquid column in the hydraulic system.

II. Experimental Set Up

In our experimental set up droplets were generated from capillary with blunt tips of a non-wetting material (silicon gel) with an inner diameter of 0.3mm and outer diameter 0.6mm.

The capillaries were connected to a tank of large enough capacity (5 litres) that enabled to maintain a constant level of liquid column during the experiment. The vessel could be placed at different levels by moving vertically the platform that held the vessel. A micrometric valve interposed between the capillary and the tank enables to adjust the flow rate at the desired value. The detached droplets were collected in a small second vessel that drained through a small tube to a large reservoir.

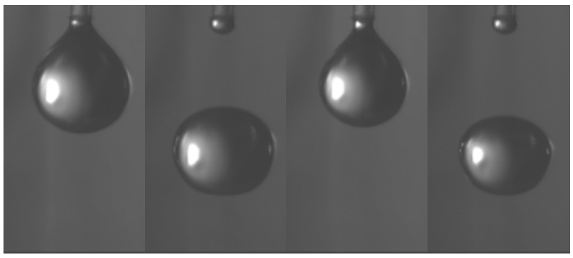

Figure 1 Photography of detaching droplets
(V=0 kV left, V=4.0kV right)

Electrification system: The meniscus used to form the droplet was electrified by induction through a cylindrical electrode (electrode geometry: 25 mm external diameter, 15 mm internal diameter, 6 mm length). The electrode was placed coaxial with capillary (this last grounded) and the distance of the upper face of this electrode to the capillary tip in our experiments was fixed at17 mm.

The electrode was connected to a DC source (0-5 kV/10W) meanwhile the liquid flowing through the non-electrical conductive capillary was earthed a few centimetres upstream the nozzle. The vessel that received the detaching droplets was also earthed.

Droplet Volume and frequency measurement device: An optical system enabled the simultaneous measurement of the volume and the frequency of detachment of the droplets. The system is based on the use of two laser sheets focused quite close to the nozzle axis and placed horizontally at different levels (6-7 mm respectively from the nozzle tip).

The lasers axis faced two photodiodes that were disposed in a hollow cavity. Horizontal slits (clearance 0.25 mm) were disposed in front of these photodiodes in order to produce a thin horizontal slice of laser on the sensor. Optical filters were also disposed in the optical axis in order to only light of the wavelength of the laser reaches the photodiode.

The signal produced in the photodiode by the laser light along time and also the variations produced by the shadow of the passing droplet was recorded in an oscilloscope with memory card and in a PC through a data acquisition card mounted. An adequate processing of this signal enabled us to determine the size of the falling droplets and the dripping period.

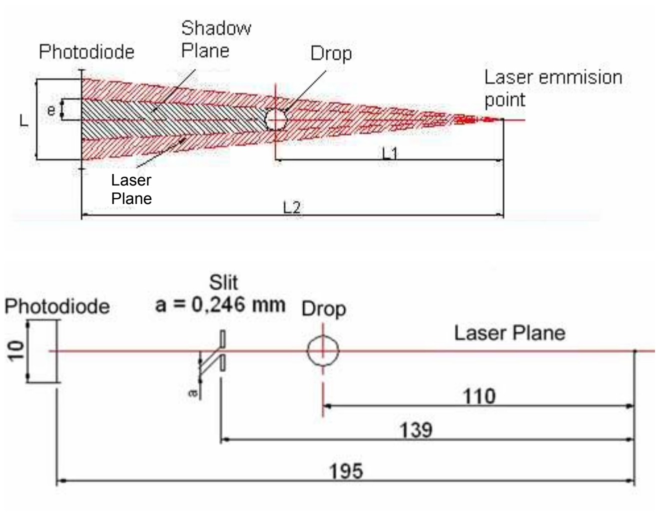

Figure 2: Details of droplet measurement system

The signals produced by two laser planes were amplified and resulted quite similar (figure 3). Both signals were used in order to determine the vertical acceleration of the electrified droplets. This magnitude was deduced from the phase difference between the two signals and is required to obtain the geometry of the falling electrified droplets. The valleys appearing close to crest of the signals correspond to the situation when the equator of the droplet traverses the laser sheets and the fraction of the light not deflected by the droplet reaches the photodiode.

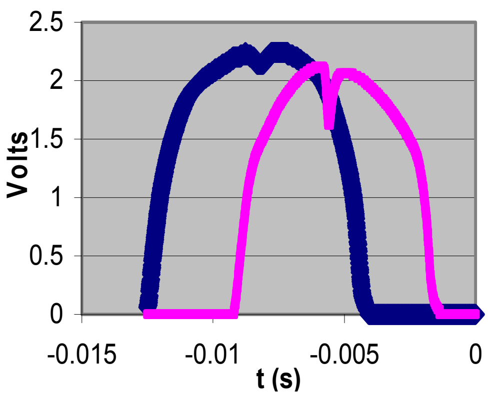

Figure 3: Signals obtained from the shadow of the flying droplet on the photodiodes

The processing of the data is based an priori on the premise that the flowing droplets present symmetry in its vertical axis and that during the passage time the droplet does not change significantly its shape.

This last assumption requires in general that the period of natural vibration of the droplets (Ronay 1977),

$$\tau = \frac{1}{F} = \sqrt{\frac{3\pi\rho V_d}{8\,\sigma}}$$

be large enough compared with the time of the passage through the laser sheets or that the damping of this oscillation that roughly is produced at a rate

$$\frac{1}{\tau_{damp}} \approx \frac{(2\pi\, F\upsilon)^{1/2}}{V_d^{\;1/3}}$$

has largely diminished the amplitude of the normal mode of vibration of the droplets when they face the sheet.

The device was calibrated with falling metallic spheres of known diameters and which enable suitable measurement of the radial coordinate of the droplets at different heights. We have determined the accuracy of the system by the contrast with the flow rate measured by pipettes and chronometers against the flow estimation through droplet volume and dripping frequency

Figure 4 shows the relative error of our measurement system.

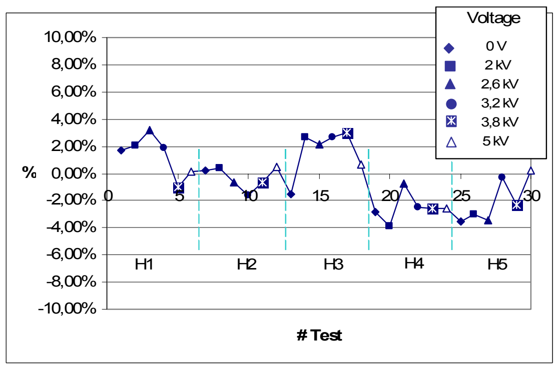

Figure 4 Error of the optical system on flow rate measurement. Tests at different liquid column height (Hi) and electrode Voltage.

As it can be observed the device enables to obtain results of a large number of droplets with a relative easy data treatment with less than a 4% of error

A more detailed description of the experimental device and data processing can be found in reference (J. Gonzalez)

III. RESULTS & DISCUSSION

When no electric field is considered prior to jetting, a periodic regime and a non-periodic one (dripping faucet regime) could be observed.

The periodic dripping regime occurred at low flow rates is characterized by constant volume droplets detached from the nozzle at constant frequency

The range for periodic dripping regime in our experiments was $0<We<1.45$.

Here $We = \dfrac{\rho U_0^2 \phi}{\sigma}$ is the non-dimensional Weber number defined with the density of the fluid (ρ), the mean velocity in the injector (U_0), the inner diameter of the capillary (ϕ) and the surface tension (σ)

Several experiments show that for non-electrified meniscus when a droplet detaches, a portion of liquid remains attached to the nozzle. This fraction of liquid may produce a smaller droplet (satellite droplet) that eventually can merge with the liquid meniscus hanging from the capillary that continues oscillating.

In our experiments we could not observe the presence of satellite droplets. When electric field was imposed, this behavior was the same as expected because in general the charges accumulated can offer a mean for controlling and eliminating satellite droplets in drop formation process (Basaran 1996).

As the Weber number was increased, a threshold was reached, above which the dripping process continues but the volume of the detached drops begin to vary from one to the next in a quasi-periodic or chaotic way. This phenomenon has been associated by other researchers to the proximity of two characteristic times: the time of relaxation of oscillations of the recoiled liquid after pinch off process and the filling time of the new droplet (Coullet 2000). Dripping faucet regime could be observed in our experiments for the range *1.45<We<1.55*.

Period of the dripping regime

In the periodic dripping regime when We is increased it is observed an increase in the dripping regime frequency as well as it is showed in the Figure 5

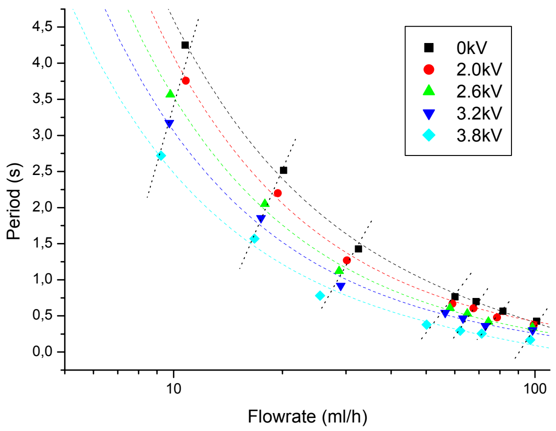

Figure 5: Dripping period as a function of flowrate: Continuous lines are the fitting of the experimental data with Scheele expression. Dahsed line links results obtained at the same liquid columns height but at different voltages.

We have compared the dependence observed of the dripping period with flow rate with the expression of Scheele (Scheele et al 1969) proposed for non-electrified meniscus. This expression was initially proposed for the determination of the volume of the detached droplets. However when dividing by the period and after a suitable reorganization, we can obtain the following expression that links the dripping period T with the flow rate Q

$$T = \frac{A_0}{Q} + \frac{A_1}{Q^{1/3}} - A_2 Q \qquad (1)$$

With

$$A_0 = \alpha_0 \frac{2\pi\sigma R}{\rho g}$$

$$A_1 = \alpha_1 \left(\frac{R^2 \sigma}{g^2 \rho} \right)^{1/3}$$

$$A_2 = \alpha_2 \frac{1}{\pi R^2 g}$$

where g is the acceleration because of gravity. The coefficients α_i are experimental factors that include the Harkins Brown correction factor (F) that accounts for the fact that part of liquid remains attached to the capillary when a "static" drop detaches from it (0.6<F<1) and the effect of the velocity profile of the liquid leaving the nozzle. This equation accounts for the contribution of gravity, surface tension, momentum flux or inertia and the effects but not for electric field effects.

Fitting of our experimental data with this expression can be observed on figure 5 where parameters α_0, α_1 and α_2 have been adjusted through least square method. As can be observed from figure 5 the dependence of the dripping period with flow rate is then satisfactorily recovered with this kind of expression

We propose here to extend the use of this experimental expression for the electrified cases. As it is expected that the electric field would impose forces on the surface of the droplet that roughly counteract the effect of the surface tension the two first parameters were enabled to vary meanwhile third parameter α_2 has been fixed in these cases to the same value that was obtained when no electric field was present. Results for this fitting are shown on table I.

TABLE I: Fitted parameters of expression (1) for different voltage intensities

	α_0	α_1	α_2
0kV	1.6	3.6	5.5
2.0 kV	1.49	2.5	5.5
2.6 kV	1.27	2.38	5.5
3.2 kV	1.13	1.99	5.5
3.8 kV	0.99	0.42	5.5

We can there observe that the parameters of the fitting have a monotonic decrease with the value of the electric field imposed on the meniscus surface indicating as expected that the charge accumulated on the surface acts as a diminishment of the surface tension value.

The dashed straight lines observed on figure 6 links points corresponding to different voltages but for a same liquid columns height.

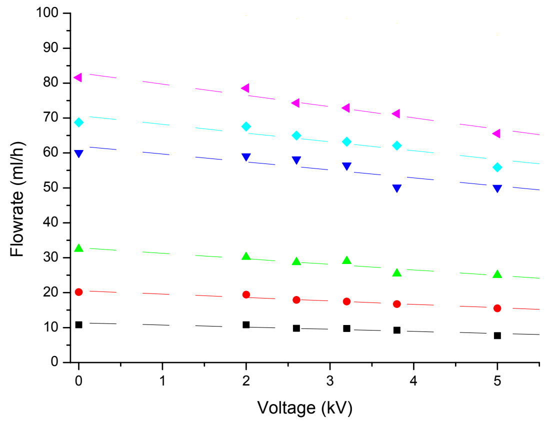

Figure 6: Flow rate variations as a function of applied voltage for fixed liquid column heights (dotted lines)

These variation in liquid flow rate are represented more clearly in figure 6 where is represented the flow rate for different liquid column heights **h** (or different energy losses produced by the micrometric valve) as a function of voltage.

As we can observe the imposition of an electric field on the meniscus and the consequent charge separation in the liquid phase requires an additional power to the system. This produces an additional energy loss in the hydraulic system and the increase of this loss redounds in a decrease of the flow rate. It is then observed that by adjusting the voltage variations in liquid flow rate of about 15 % are possible in a wide range of flow rates.

This diminishment in flow rate for a given liquid column height associated to the electric field imposition is produced by a decrease in the volume of the droplet formed. This can be observed on figure 7 that

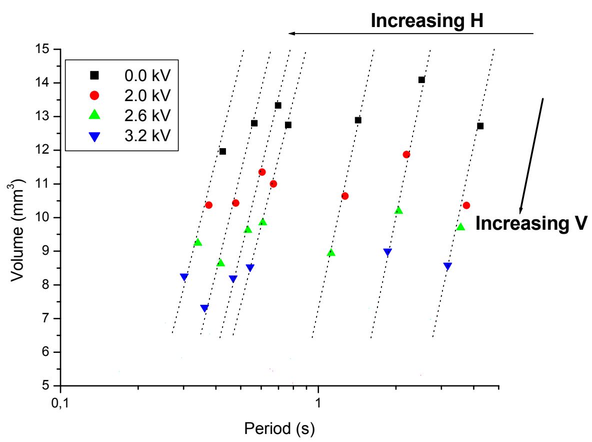

Figure 7: Volume of the droplets as a function of dripping period for different voltages. Dotted lines correspond to constant liquid column height.

The increase of droplet frequency when electric field is imposed that accompanies this process dampens to a certain extent this effect, as it tends to increase the flow rate.

As can be seen in this figure, those points from corresponding to same liquid column height and different voltages disposed aligned in a semi logarithm coordinate axis.

IV. Conclusions

We have analyzed in this article the alteration of the dripping phenomena under periodic regime of detaching droplets that are electrified by induction.

The condition imposed in the hydraulic system that enables the droplet formation is a constant liquid column height.

Under this condition of droplets electrification, we found consequences in the flow rate, in droplet volume and on the dripping period. We have proposed to analyze the link between these magnitudes.

The use of a rearranged expression of Scheele linking flow rate with dripping period has been adopted to fit non electrified and also electrified droplets. A good fitting of the experimental data could be observed by letting the surface tension terms to be modified by the charged lying on the meniscus surface.

Electrification of the meniscus gives also a reduction of the flow rate that can be associated to an additional loss of energy required to the system to separate charges. This energy loss acts as an additional head loss in the hydraulic system produced at the nozzle exit. The diminishment in flow rate is produced by a decrease in droplet volume a process that is accompanied by an increase of the dripping period

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