Electrohydrodynamic induced wave-collision on a liquid jet

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A pulsating DC electric potential is used to control the spraying of tap water and polyvinyl alcohol aqueous solutions in order to produce monosized droplets. Setting up a suitable electrode geometry and using an appropriate pulsating DC electric potential and frequency, it is possible to control the wavelength of the axisymmetrical wave. This wave travels downstream along the liquid jet and grows in amplitude until the liquid jet breaks up. There exists a range of frequencies within which the frequency of droplet production and the frequency of the pulsating DC electric potential used are directly proportional to each other. This frequency range is named the synchronous region where one droplet is produced for each crest of the axisymmetrical wave. Within the synchronous region an increase of the pulse frequency leads to a reduction of the wavelength of the axisymmetrical wave, which in turn causes the droplet size to decrease. The wavelength and thus the droplet size decreases to a certain limit, beyond which control of the axisymmetrical wave becomes impracticable. It is observed that, within the synchronous region above a certain frequency, collisions between two successive axisymmetrical waves occur. This frequency is named the collision frequency, f_c, where only one droplet is produced from two successive wave crests of the liquid jet. Since one drop is produced when the two wave crests collide, different sized droplets will be formed above the collision frequency, thus monosized droplets are not usually produced above f_c. It is also observed that the value of f_c depends on the liquid viscosity. Above f_c the likelihood of collisions between wave crests increases linearly as the pulse frequency increases such that the number of droplets produced per unit time remains the same.

1. Introduction

The break-up of a jet by varicose instability occurs when on the liquid jet surface there are waves that propagate in an axisymmetric mode (i.e. axisymmetric waves). These waves propagating and growing in amplitude along the jet in downstream direction induce the break-up of the liquid jet into droplets. Varicose instability has been studied by a number of researchers. Plateau as revised by Worthington [1], proposed that the equilibrium of a free cylinder made of any liquid under the influence of a surface tension, becomes unstable as soon as the length of the cylinder, l_c, exceeded π times the diameter, d_c, of the cylinder. Lord Rayleigh [2] presented a theory based on infinitesimal disturbances for liquid jet in which the liquid viscosity can be neglected. Weber [3] derived a theoretical analysis of the break up of a liquid jet which viscosity cannot be neglected. A more comprehensive and complex analysis was made by Basset [4] who investigates the effect of surface tension, viscosity, density, surrounding air and static electric potential on the liquid jet break up by varicose instability. More recently others investigators among which Schneider *et al.* [5], Taylor [6], Neukermans [7], Mutoh *et al.* [8], Bailey and Balachandran [9], Cloupeau and Prunet-Foch [10], Turnbull [11] and Hartman [12] have focused their research on the effect of a static electric potential on the liquid jet break up by varicose instability with different results about the role played by the electric potential on the liquid jet break up.

Investigation on the effect of a non-static electric potential on the liquid jet break up have been performed by Sato [13], who used an applied voltage with four different types of wave pattern such as AC sine wave, a rectified negative AC, a positive sine wave and a positive square pulse wave in order to control the spraying. Further studies on the effect of a non-static electric potential on the liquid jet break up have been performed by Balachandran *et al.* [14] and Huneiti *et al.* [15-17]. This researchers used as a non-static electric potential a AC potential superimposed on a DC potential in order to control the liquid jet break up. The idea of using a non-static electric potential in order to control the spraying lays in the possibility of controlling the wavelength of the axisymmetrical waves, which are responsible of the liquid jet break-up and thus to control the droplet diameter when the liquid jet breaks up into droplets.

The main purpose of this study is to investigate the effect of the frequency of a pulsating DC potential on the liquid jet break up of tap water as well as on the break up of jets made of highly conductive and viscous liquids.

2. Spraying arrangements

The apparatus used to perform the experiments is a simple configuration consisting of a stainless steel nozzle positioned in vertical direction below which is placed a metallic annular disk, see Figure 1. The characteristic of the electrode configurations is reported in Table 1.

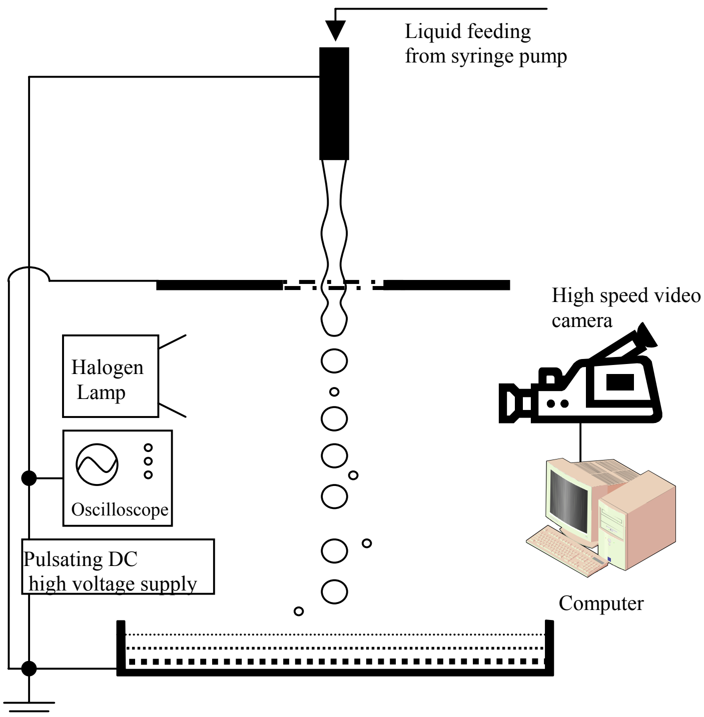

Fig. 1 Experimental set up used in this work.

Table 1 Electrode configurations.

Nozzle diameter		Distance nozzle to earth electrode (mm)	Hole diameter (mm)
I.D. (mm)	O.D. (mm)		
1.1	1.4	5	6

A high voltage supply (EHT) is attached to the nozzle, while the metallic disk is earthed. The liquid is pumped to the nozzle using a syringe pump Harvard Apparatus 22 Model 55-2222. The highly viscous liquids used have been prepared by adding polyvinyl alcohol to water. The properties of the water solutions used are reported in Table 2. The flow rates used is 32.2 ml/min. The power supply used is a high voltage source Nada Electronics model 2300, which was used to generate a high pulsating DC voltage of 4 kV with a frequency ranging between 30-260 Hz. The spraying process was recorded using a high-speed digital video camera model Kodak Ektapro HS 4540 with a Leica Monozoom 7 lens.

Table 2 Physical properties of the polyvinyl solutions used in the present work.

Liquid	Electrical Conductivity (S/m)	Viscosity (mPa s)	Surface tension (mN/m)	Density (kg/m^3)
Tap water	0.1	1	72	1000
PVA 3% wt	0.048	40	62	1002
PVA 5% wt	0.093	140	58	1009

The recorded images were downloaded into a PC and later processed by software called "Optimas" for the determination of droplet size and formation frequency. Halogen lamps were used for lighting the rig, illuminated either the front or the rear for conventional or shadow photography respectively. Each experiment took only few minutes and hence avoiding a long exposure of the jet to the light, which could change the viscosity of the liquid by heating it up. The experiments were conducted at room temperature.

3. Effect of the pulsating DC frequency on the droplet formation

Liquid jet break-up into droplets may occur by the growth of surface axisymmetrical waves in the absence of other influential factors. The application of a time-varying electric field (e.g. pulsating DC potential) to the liquid jet generates time-varying stresses on the liquid surface and those stresses can be opportunely used in order to instigate the formation of surface axisymmetrical waves with appropriate wavelength. Therefore, using a pulsating DC potential it is possible to control the droplet size distribution by controlling the wavelength of the axisymmetrical waves Speranza *et al.* [18]. Within the range of pulsating DC frequencies where the control is possible, it is observed that, for each pulsating DC cycle a droplet may be formed and that to the frequency increase the droplet diameter reduces until a certain point over which the mechanism of droplet formation become poorly defined. The range of frequencies in which there is synchronism between pulsating DC frequency and droplet formation frequency has been termed by Sato [13] as the synchronous frequency region.

In order to understand the reason why an increase in the applied frequency beyond a certain values leads to poorly defined mechanism of droplet formation, it has been suggested by Balachandran [19] to determine how the frequency of the droplet changes with the applied frequency. This was performed using the electrode configuration above cited and using as liquid tap water, PVA 3% and PVA 5%. Each of these liquids has a characteristic frequency range within which it is observed that the relationship between the applied frequency and the droplet frequency is one-to-one, as shown in Figure 2.

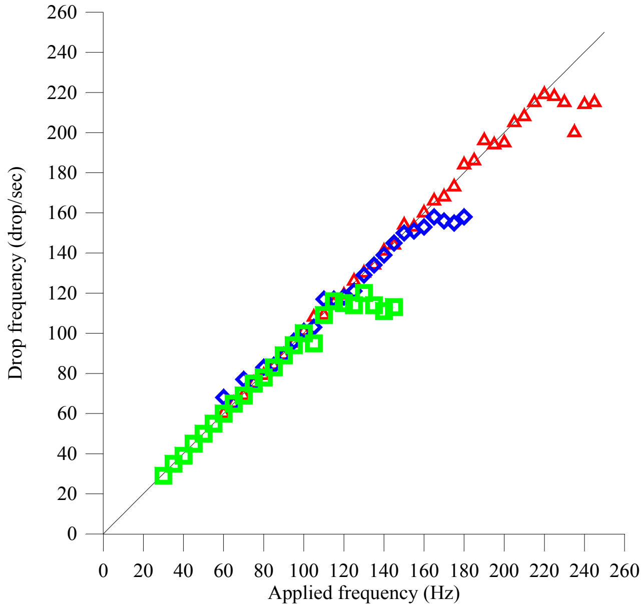

Fig. 2 Droplet frequency as a function of the applied pulsating DC frequency. △: water; ◇: PVA 3%; □: PVA 5%; —— : one-to-one relationship.

This relationship is valid for tap water in the frequency range 60 to 220 Hz. Over 220 Hz an increase in the frequency does not linearly produce an increase in the droplet frequency. Rather the droplet frequency seems to reach a plateau. The same phenomenon is observed when PVA 3% and PVA 5% are atomised, but in these cases the deviation of the droplet frequency from the applied frequency occurs at about 155 Hz and 115 Hz for PVA 3% and PVA 5%, respectively, as shown in Figure 2.

The reason why an increase in the applied frequency over a certain value does not cause any further linear increase in the droplet frequency may be explained by analysing Figure 3. Following the record numbers written on Figure 3, it can observed from record number 1 to number 7 that the axisymmetrical wave travels regularly along the jet with a well-defined wavelength. In number 8 and 9 the regular wave pattern suddenly changes, as a bump (b) is observed to travel faster than the one (a) that is preceding it. In record numbers 10-13 the faster bump (b) is merging with the bump (a) well before the jet break-up occurs. Record number 14 shows the jet breaks up and creates a droplet whose shape can be assimilated to a Cassini oval prolate. In record number 15, the oval has become a spheroid and the coalescence is completed. From record numbers 16 to 18, the axisymmetrical wave starts again to regularly travel along the jet with a well-defined wavelength. Therefore, from two bumps (a) and (b) a single droplet is produced. This phenomenon occurs periodically and more frequently as the frequency increases beyond a certain value of the frequency named collision frequency, f_c. The f_c for water, PVA 3% and PVA 5% are 220 Hz, 155 Hz and 115 Hz respectively. So, the above shown phenomenon can be accounted for mismatch between applied frequency and the droplet frequency when the applied frequency goes beyond f_c. As stated, the phenomenon just described for a liquid jet of water is also observable with the same modality in the case of PVA 3% and PVA 5% and in this last case a detailed sequence of the coalescence or collision between two bumps within the liquid jet is given in Figure 4.

The mechanism of collision may be qualitatively explained by comparing the break up time and the time between two consecutive bumps. The time between two consecutive bumps, t_f, is equal to the inverse of the frequency whereas the break up time can be evaluated as following: $t_{break-up} = \frac{1}{q}\ln\left(\frac{r_{j0}}{\delta^*}\right)$ where r_{j0} is the radius of the jet for $t=0$, δ^* is the initial disturbance and q is the growth factor [20]. Evaluation of the break up time is quite difficult because it is needed the estimation of the value of the initial disturbance, δ^*, which is depending from a numbers of parameters such as the physical properties of the liquid sprayed, the nozzle used and the characteristic of the electrode set up. Also, another factor that is very difficult to be evaluated is the growth factor for an electrified liquid by a pulsating DC potential.

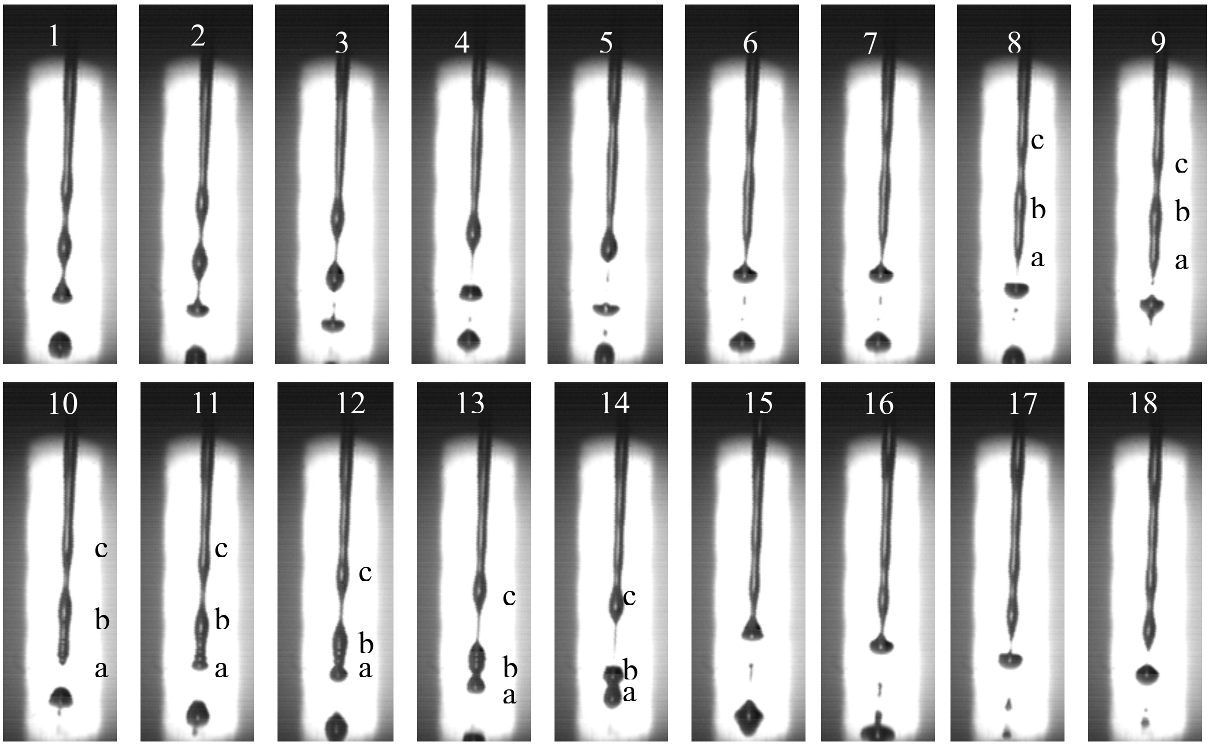

Fig. 3 Spraying of water by a pulsating DC potential with a frequency of 260 Hz

However, an approximate calculation for a qualitative discussion of the mechanism involved in the wave collision phenomenon may be performed, considering a growth factor for a non electrified liquid jet [3] and giving a arbitrary initial disturbance of about to the 5% of the jet radius [12]. As stated, the time between two bumps is equal to the inverse of the frequency. Therefore, on one hand, when the frequency increases, the wavelength reduces and thus the time between two consecutive wave bumps also decrease hypothetically to zero for infinite frequency, see Figure 5 curve t_f. On another hand, to the frequency increase and thus to the wave number increase (when the frequency increase the wave length decrease) the break-up time decrease until to reach a minimum value over which any further frequency increase leads the break-up time to increase again as show in Figure 5 curve $t_{break-up}$. Therefore, it may occur that for specific values of the liquid jet surface charge, liquid physical properties and electrode geometries there is a range of frequency in which the break up time is either equal or larger than the time between two consecutive bumps. In this range of frequency the wave bump may reach to the jet end before that the previous bump has been pulled out as droplets and it collide with it.

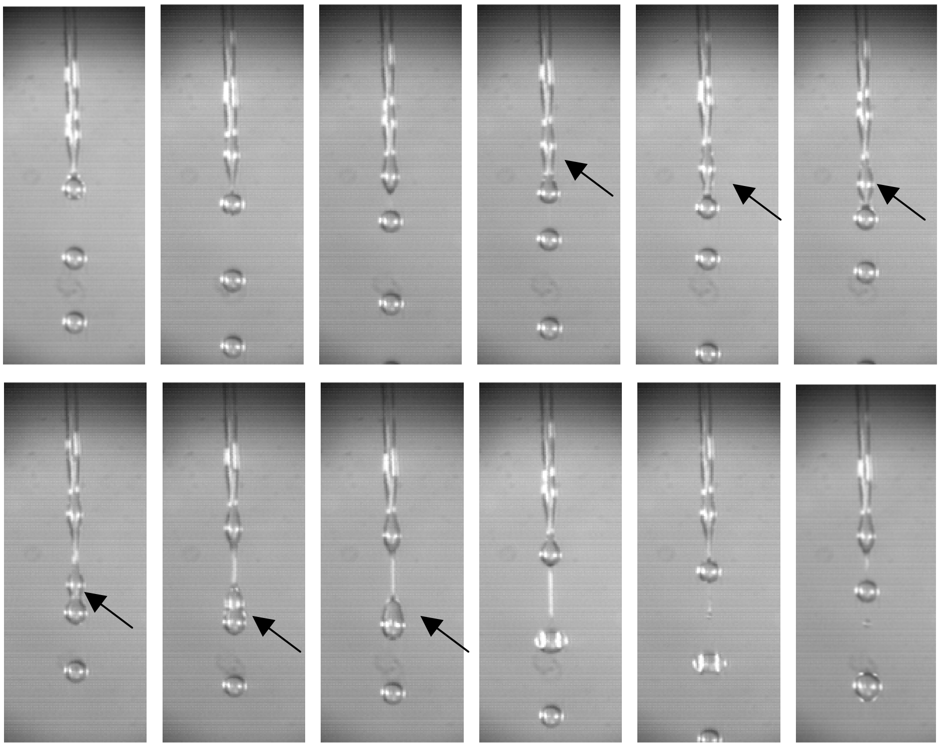

Fig. 4 Spraying of PVA 5% by a pulsating DC potential with a frequency of 130 Hz, where waves starting later in time catch up with earlier waves

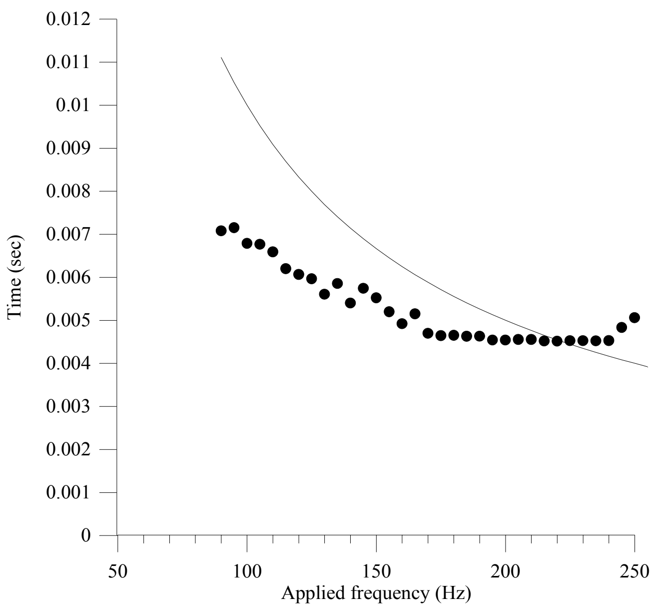

Fig. 5 Time between two consecutive bumps and $t_{break\text{-}up}$ versus applied frequency for tap water.

● is $t_{break\text{-}up}$; ——— is the time between two consecutive bumps

4. Conclusion

The use of a pulsating DC potential permits the control of the frequency of droplet formation in such way that within the synchronous frequency region for each DC pulse a droplet is formed until a value of the pulse DC frequency, f_c, beyond which wave-collision occurs. Above f_c the likelihood of collisions between waves crests increases linearly as the pulse frequency increases such that the number of droplets produced per unit time remains the same. It has been show that f_c is depending from the liquid viscosity in a way that to the liquid viscosity increase f_c decrease. When a pulse DC frequency higher of f_c is used in order to drive the liquid jet break up from two waves bump a droplet may form because of wave-bang and this phenomenon may represent a limit for this technique liquid spraying.

4. References

[1] Worthington A M 1879 *Philos. Mag.* **XXX** 49-61

[2] Lord Rayleigh F R S 1878/1879 *Proc. of the Roy. Soc. of London, Series A* **10** 4-13

[3] Weber C 1931 *Angew. Math. Mech.* **2** 136-155

[4] Basset A B 1894 *J. Math.* **16** 93-110

[5] Shneider J M Lindblad N R Hendricks Jr. and Crowley J M 1967 *J. Phys. D: Appl. Phys*. **38** 2599-2605

[6] Taylor G. 1969 *Proc. of the Roy. Soc. of London, Series A* **313** 453-475

[7] Neukermans A 1973 *J. Phys. D: Appl. Phys*. **44** 4769-4770

[8] Mutoh M Shozo K and Kamimura K 1979 *J. Phys. D: Appl. Phys*. **50** 3174-3179

[9] Bailey A G and Balachandran W 1981 *J. of Electrostatic* **10** 99-105

[10] Cloupeau M and Prunet-Foch B 1989 *J. of Electrostatic* **22** 135-159

[11] Turnbull R J 1992 *IEEE Trans. on Industry Appl.* **281** 432-1438

[12] Hartman R 1998 Electrohydrodynamic atomisation in the cone-jet mode. From physical modelling to powder production. PhD Thesis at Delft University The Netherlands

[13] Sato M 1984 *J of Electrostatic* **15** 237-247

[14] Balachandran W Machowski W and Ahmad C N *IEEE Trans. on Industry App.* **30** 850-855

[15] Huneiti Z Balachandran W Burrough S 1996 12th European Conference of ILASS on Liquid Atomisation and Spray System 107-114

[16] Huneiti Z Balachandran W and Machowski W 1997 *J. of Electrostatic* **40&41** 97-102

[17] Huneiti Z Balachandran W and Machowski W 1998 *IEEE Trans. on Industry Appl.* **34** 279-285

[18] Speranza A Ghadiri M Newman M Sesti Osseo L and Ferrari G 2001 *J. of Electrostatic* **51-52** 494-501

[19] Balachandran W Speranza A Ghadiri M 2001 Private communications

[20] Lefebvre A H 1989 *Atomization and sprays* (London: Hemisphere Publishing corporation)