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poświęcone są publikacjom naukowym z zakresu teorii i badań doświadczalnych w dziedzinie mechaniki i termodynamiki przepływów, ze szczególnym uwzględnieniem problematyki maszyn przepływowych

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Gdańsk

Morphological Studies of Electrodynamic Spraying of Water

Electrodynamic spraying of liquids is caused by the electric force applied to the surface of liquid. The results of phenomenological studies of the process of disruption of the liquid surface and the modes of spraying are reported. Distilled water was used as the test medium. The water was forced through a metal capillary connected to a high dc voltage. The microscopic observations of the jet in the pulsating light reveal a number of phenomena which have previously not been reported.

1. Introduction

The spraying of liquids employing electric forces has been known since the first observations of Bose in 1745 [1,2]. The results of his experiments have been forgotten for more than a century, and the phenomenon rediscovered in 1882 by Rayleigh [3], who determined the instability criterion for charged liquid droplets. Zeleny in 1917 [4] estabilished the criterion for instability of an electrified liquid at the tip of a capillary. Many years later Vonnegut and Neubauer [5] considered the initial and final states of the spraying process, and using the energy minimization principle predicted the most probable charge-to-mass ratio of the produced droplets. Drozin in 1955 [2] considered the electrical forces causing instabilities of the liquid surface as arising from stresses in the dielectric liquid. Taylor in 1964 [6,7] predicted theoretically the cone-jet shape of the meniscus of liquid issuing from a capillary. Shorey and Michelson in 1970 [8] found the conditions which should be satisfied by the liquid to be sprayed effectively.

In the last two decades a number of papers have been published on this subject. However due to the numerous parameters, such as: liquid flow rate, conductivity, dipole moment, permittivity, surface tension, viscosity, surrounding gas pressure, its ionization, diameter of a capillary etc., more or less influencing the disruption process, the results of liquid spraying are different as reported in different papers. The differences refer mainly to the liquids of conductivity in an intermediate range, i.e. from 10^{-4} to 10^{-8} Ωm, and in particular to the distilled water.

However, many theoretical and practical questions remain still unanswered:

- In which range of electric conductivity the liquid can be sprayed as fine aerosol?
- Is it possible to synchronize the electrodynamic spraying with the aid of an alternating electric field? Is the mechanism of such spraying similar to that obtained by the dc excitation?
- Why the spraying at negative polarity differs from that at positive?
- What is the role of the corona discharge from the water surface in the electrodynamic spraying?

A growing interest in physical backgrounds of the electrodynamic spraying is forced mainly by its new applications such as ink-jet printing, painting, fuel atomization in combustion systems, emulsifications, microincapsulations, crop spraying, charged droplets scrubbing etc., which are now either widely used or are belived to allow to increase the effectiveness of the number of technological processes.

Recently some attempts were taken to summarize the knowledge on the spraying process. The spraying modes have been systematically described by Hayati et al [9] and Cloupeau and Prunet-Foch [10]. These modes are common for different liquids at certain spraying conditions, although some other events and sub-modes can also be observed.

The purpose of the present paper is to characterize the spraying process in terms of the fluid dispersing system and the charging voltage. The experiments are restricted to the spraying of distilled water in a system comprising a metal capillary fed by a hv dc source of positive and negative polarity. The experiments are carried out at ambient air at temperature of about 20°C. The liquid is forced through the capillary at a constant hydrostatic pressure.

2. Experimental stand

The schematic diagram of the experimental set up used for studying the electrodynamic dispersion of liquids is shown in Fig. 1. The dispersion system consist of a metal capillary (hypodermic needle of external diameter of 0.9 mm and internal diameter of 0.65 mm) placed vertically and supplied from a high voltage source and a grounded flat brass electrode of diameter 300 mm, with rounded edges. The capillary is connected to a container in which a stable constant level of water is maintained in order to keep a constant hydrostatic pressure at the tip of the capillary. The distance between the capillary tip and the counter plate is $d = 50$ mm.

The capillary protrudes from a stainless steel plate biased at the same potential as that of the capillary. The diameter of the plate is of 120 mm. This electrode screens the tip of the capillary from external electrostatic fields, which could induce a spurious charge on the surface of the issuing liquid, particularly when low bias potential is applied.

The lower plate is grounded through a microammeter which measures the total current carried by the water droplets and ionized gas molecules. In this plate a small slot of 5 mm in width is made, in order to allow a part of the total number of droplets to fall into instruments measuring their size and charge. The droplet size distribution was determined by means of the droplet size analyzer of AWK type. The total number of at least 4000 droplets was classified in 128 groups. Charge on the droplets was measured by means of a cylinder probe described by the authors in the papers [11,12] or alternatively by a Faraday cage.

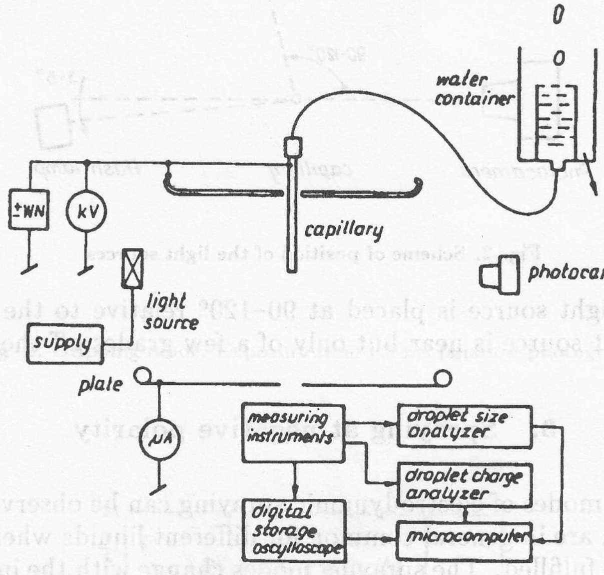


Fig. 1. Experimental stand

The water level in the container can be changed. It was kept at 20 mm above the capillary tip. This water level is slightly below the level at which the hydrostatic pressure and the surface tension forces are in equilibrium, and no dripping occurs then.

Many photographs were taken in order to learn more about the dispersion process. The tip of the capillary was photographed using the shadow photography in the light pulses produced by the Xenon lamp of the flash duration time of about 3 μs or a commercial flash lamp with the light pulses of duration of about 1.5 ms. Additionaly the photographs in continuous light were taken in order to notice the spatial distribution of the produced aerosol. Attempts to photograph the sequences in electrodynamic spraying were unsuccesful due to lack of a high speed photo camera.

An original method has been developed and applied to take some unique photographs. Both, the permanent lighting and the light pulse of the duration of 3 μs were applied simultaneously. The method allows to observe on one photograph the particle shape, its position and the trajectory of the particle as well. Bright traces on the photographs are the effect of the permanent light scattering on a droplet, at the time exposure of 1/30 s. Dark dots are shadows of droplets in the pulse light of 3 μs duration. The scheme of the light sources position is shown in Fig. 2.

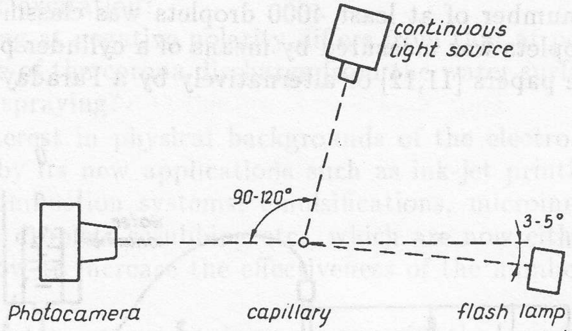


Fig. 2. Scheme of position of the light sources

The permanent light source is placed at 90–120° relative to the lens axis while the pulsating light source is near but only of a few grades off the axis.

3. Spraying at negative polarity

The following modes of electrodynamic spraying can be observed in our spraying system, which are in general common for different liquids when certain spraying conditions are fulfilled. The spraying modes change with the increasing potential applied to the capillary through which the distilled water is flowing. Within these spraying modes some sub-modes can be distinguished. Although they are similar in general to each other, some differences in formation of the liquid jet have been observed. Some of these sub-modes have hitherto not been reported on.

3.1. The dripping mode (Fig. 3)

The liquid drips from the capillary with a constant frequency N, which increases nearly exponentially with the voltage increasing (Fig. 4). The droplet diameter decreases steadily as the potential rises (Fig. 5).
From the voltage higher than about −8.2 kV up to about −9 kV the main drop can be accompanied by a small satellite (sibling) droplet or a few droplets (Fig. 6) of number and size depending on the spraying parameters and the applied voltage. At about −9 kV the charge Q of each droplet approaches the Rayleigh charge limit Q_r (Fig. 7) and from each droplet a series of smaller droplets is emitted. As the potential of the capillary increases further from −9 kV up to about −11.5 kV the droplet elongates to an elipsoidal thick filament and the liquid is ejected

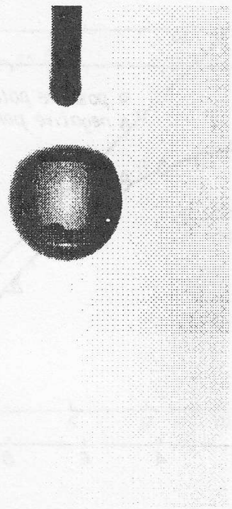


Fig. 3. Dripping mode. Exposure time 1.5 ms (shadow photography)

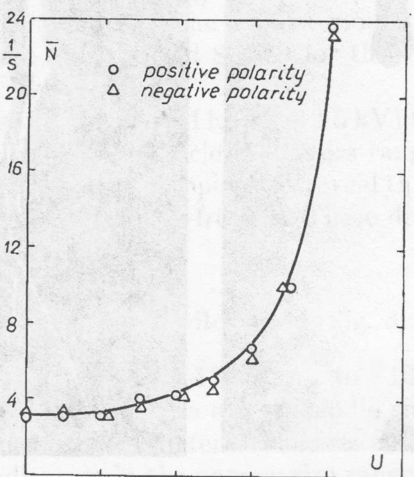


Fig. 4. Dripping frequency as a function of applied voltage. Pressure p=80 mm H_2O

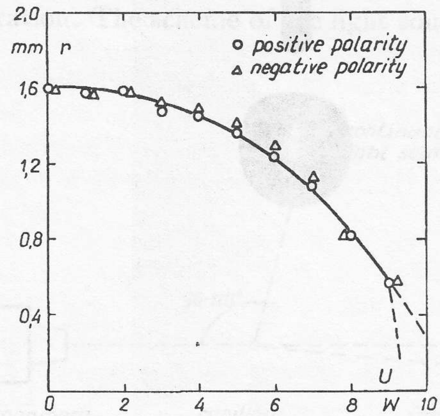
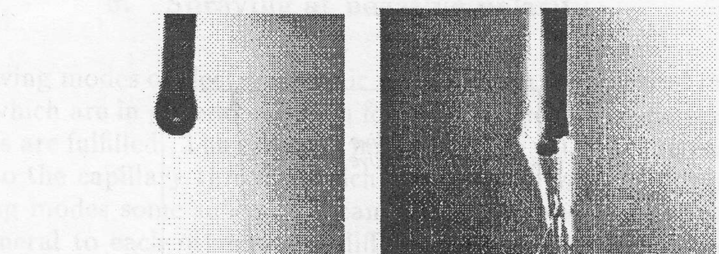


Fig. 5. Diameter of droplets issuing from a capillary at high voltage. Pressure p=80 mm H_2O



a) b)

Fig. 6. Dripping mode with sibling droplets. Exposure time 1.5 ms (shadow photography) (a), exposure time: 3 μs+1/30 s (b).

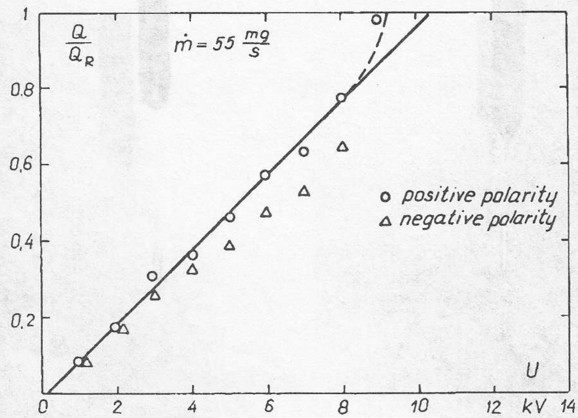


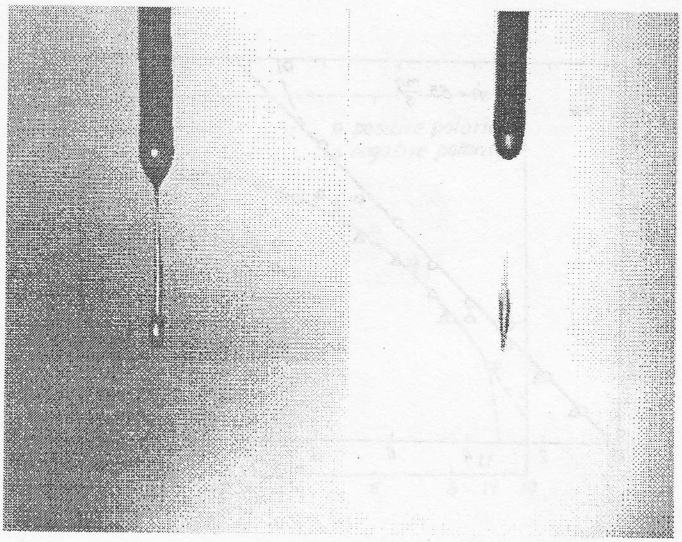
Fig. 7. The ratio of actual droplet charge to the Rayleigh limit. Pressure p=80 mm H_2O

from the front of the pendant drop. The filaments breaks off and the liquid meniscus relaxes repetitively back to its initial shape. From the filament one of a few sibling droplets are formed. The frequency of droplet production rate can increase by one or two orders of magnitude compared to that of the dripping mode. The spraying is bimodal and the droplet modal diameters range from 900 μm and 100 μm down to 600 μm and 80 μm for the voltage increasing from −9 up to −12 kV respectively.

As the voltage increases further (−11.5 to −13.5 kV) the structure of dispersion becomes polydisperse, with the particle diameters ranging fron 100 μm to 1000 μm. The observations in the stroboscopic light reveal that the meniscus elongates, and the irregular droplets are ejected from it. These droplets can disrupt further into smaller droplets.

3.2. Spindle mode (Fig. 8)

At the negative potential from −13 kV up to −16 kV the spindle mode is observed. At the tip of the capillary a single spindle shaped jet is formed, which next falls off. The increase in the potential causes a slight elongation of the jet. The droplets are monodisperse in the narrow size range from 400 to 500 μm. The siblings previously observed cease almost completely. The droplets are spread in an irregular manner around the capillary axis.
Above −16 kV the spindle mode is no longer monodisperse and becomes bimodal. Two sizes of droplets are distinquished: the first one of diameter of about 600 μm and the second one of diameter below 100 μm. With the voltage increasing the



a) b)

Fig. 8. Liquid spraying at the voltage –15 kV. Exposure time 3 μs (a), 1.5 μs (b).

modal diameter of the larger droplets also increases, but the number of droplets ceases. The small droplets are more numerous but their diameters only slightly decrease.

3.3. Thread-drop mode (Fig. 9)

Above –21.3 kV a thick jet of the diameter approximately equal to the internal diameter of the capillary issues from the capillary. At the head of the jet a large drop is formed, and behind it the jet elongates to a fine thread. As the thread becomes several millimeters long it breaks up into a number of small droplets. The diameter of the thread evaluated from the photographs is of about 100 μm. Although the jet formation changes qualitatively compared to the spindle mode, the significant changes in the droplet modal diameters have not been observed. The number of the fine droplets increases with the voltage increasing. The size of the main large droplets increase steadily with the increase in voltage, but their fraction in number size distribution decreases.

No other spraying modes have been observed for negative voltages increasing up to –40 kV.

In Fig. 10 the droplet modal diameter D_{mod} as a function of voltage is presented. The solid line refers to the modal diameter, while with dashed lines the bandwidth FWHM is indicated. Only in the voltage range from –11.5 kV to –13.5 kV where no modal value can be distinguished, the solid line is omitted.

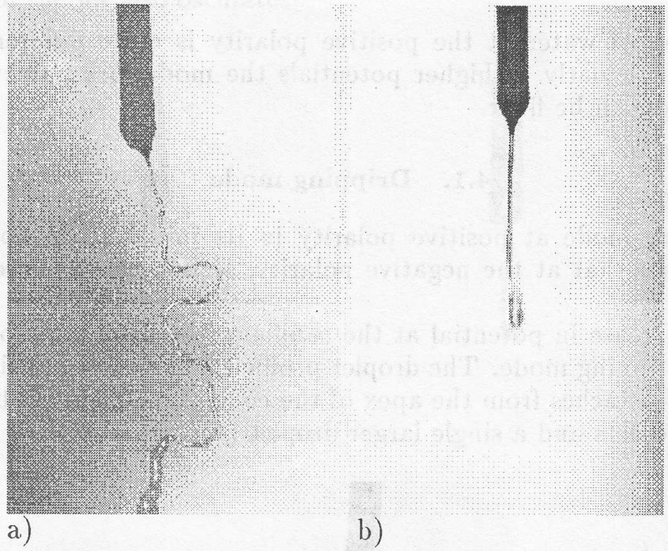


Fig. 9. Liquid spraying at the voltage –22 kV. Exposure time 3 μs (a), 1.5 μs (b).

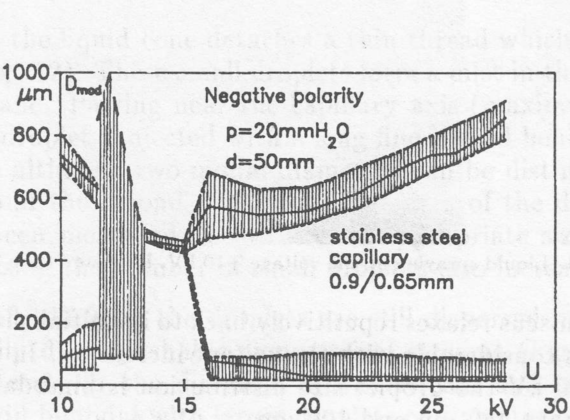


Fig. 10. The modal diameter and bandwidth (FWHM) as a function of negative voltage. Electrode distance d = 50 mm. Capilary: external diameter 0.9 mm, internal diameter 0.65 mm

4. Spraying at positive polarity

The spraying of water at the positive polarity is quite different from that at negative. Particularly at higher potentials the modes are numerous and the produced aerosol can be finer.

4.1. Dripping mode

The dripping mode at positive polarity in its initial stage does not differ significantly from that at the negative polarity, so one can refer to the section 3.1.

With the increase in potential at the capillary, the dripping mode developes into the microdripping mode. The droplet profile elongates to an ellipsoidal thick filament, which detaches from the apex of the cone. The filaments break up to a series of fine droplets and a single larger droplet (Fig. 11).

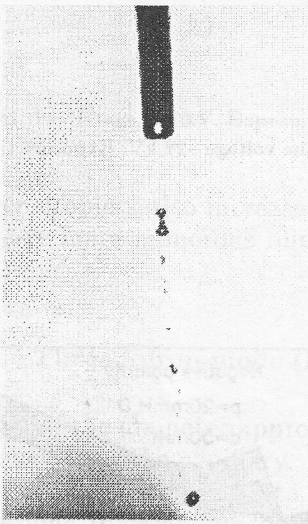
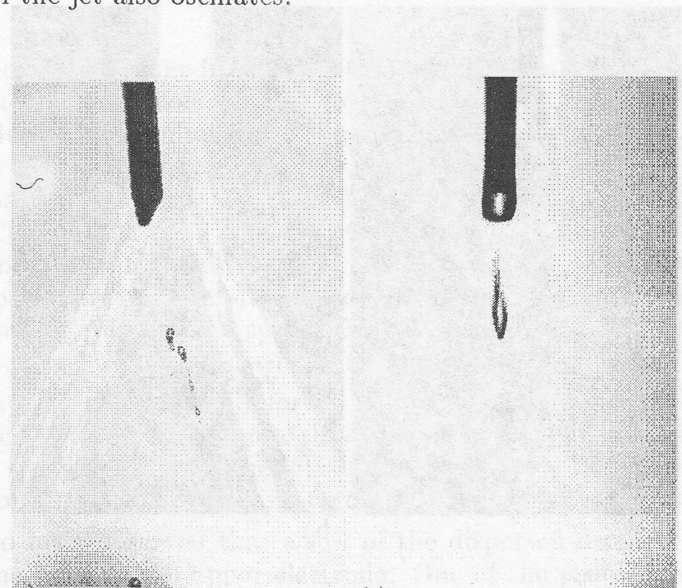


Fig. 11. Liquid spraying at the voltage +10 kV. Exposure time 3 μs

Then the liquid meniscus relaxes repetitively back to its initial shape. The number of siblings increases considerable with the voltage increasing. In the voltage range from +9 kV to +10 kV the droplet size distribution is bimodal, and the modal diameters are of about 450 μm and 100 μm.

4.2. Spindle mode (Fig. 12)

At positive potential the spindle mode is observed in the voltage range from +10.7 kV to +17.2 kV. At the tip of the capillary a single spindle shaped jet is formed, which next falls off. The increase in the potential causes a slight elongation of the liquid jet. Unlike the spraying at negative polarity, the jet oscillates in a stable plane, which can turn sometimes to another stable position. The lenght of the jet also oscillates.

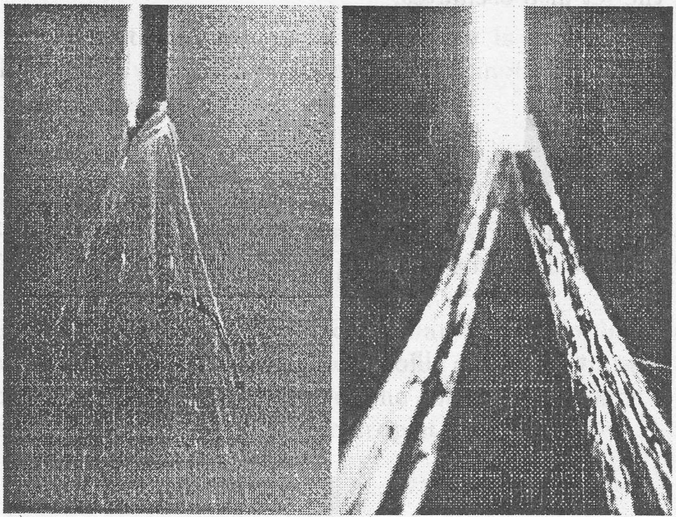


a) b)

Fig. 12. Liquid spraying at the voltage +12 kV. Exposure time 3 μs (a), 1.5 μs (b).

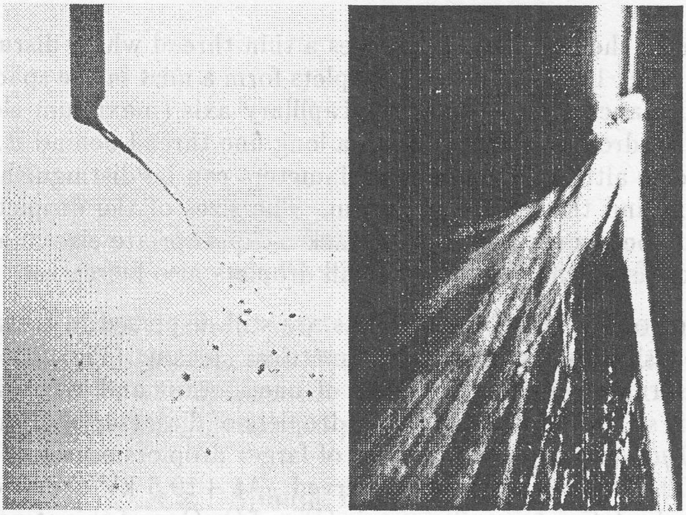
Sometimes from the liquid cone detaches a thin thread which disrupts into a few fine droplets (Fig. 12). These small droplets form a mist in the space between the capillary and plane. Passing near the capillary axis (maximum electric field), a small coma-like droplet is ejected with a long fine thread behind it. The droplets are polydisperse although two modal diameters can be distinguished, the one of about 200 μm and the second of 30 μm. The sizes of the droplets forming the mist have not been measured due to lack of appropriate size analyzer. As the voltage is increasing the number of small droplets also increases.

At the voltage of +17.2 kV the droplets are still dispersed in a stable plane but only in two easily distinguishable symmetrical streams (Fig. 13). The spindle is formed alternately in the direction of one stream and the other. The size distribution is still bimodal with larger droplets of diameter of about 200 μm and smaller of 30 μm although the number of larger droplets ceases with the voltage increasing. The mist is no longer observed. At +19.5 kV the streams becomes unsymmetrical relative to capillary axis (Fig. 14). One of this streams consists of a small number of large droplets of diameter of about 200 μm, which are formed from the spindle. The droplets in the second stream arise from disruption of a fine thread ejected from the second spindle. The small droplets are of diameter of about 30 μm.



a) b)

Fig. 13. Liquid spraying at the voltage +18 kV. Exposure time 3 μs + 1/30 s (a), 1/30 s (b).



a) b)

Fig. 14. Liquid spraying at the voltage +22 kV. Exposure time 3 μs (a), 1/30 s (b).

4.3. Con-jet mode

Within the voltage range from +24 kV to +28 kV liquid issuing from the capillary takes the form of a cone with a fine elongeted jet issuing from its apex. By observations in the light pulsating with frequency of about 100 Hz and with pulse duration of 3 μs it was estabilished that the thread rotates round the capillary axis (Fig. 15a). At its end the thread becomes finer and takes the spiral form (Fig. 15b). This spiral thread disintegrates into small droplets. The droplets are spread winding round the mother spiral (i.e. the second spiral is superimposed on the first one). In the light of long duration pulses (1.5 ms), the spreading droplets resembles a developing spiral (Fig. 15c). The fine droplets of the mean diameter of 30 μm are produced within this mode.

The aerosol is dispersed nearly uniformly in the spraying cone round the capillary axis. The size distribution does not change significantly with the voltage within this mode of spraying. In this mode a hysteresis has been observed. The onset voltage is about +24 kV, but the mode extinguishes at about +20.5 kV.

It has also been observed that a few of the dispersed droplets are attracted from the plane back to the upper electrode. One of the probable explanation is that the droplets approach the water surface, contact with it, but if they are not captured due to the surface tension they are recharged in the existing electric field and forced upward. This hypotheses needs however further investigations.

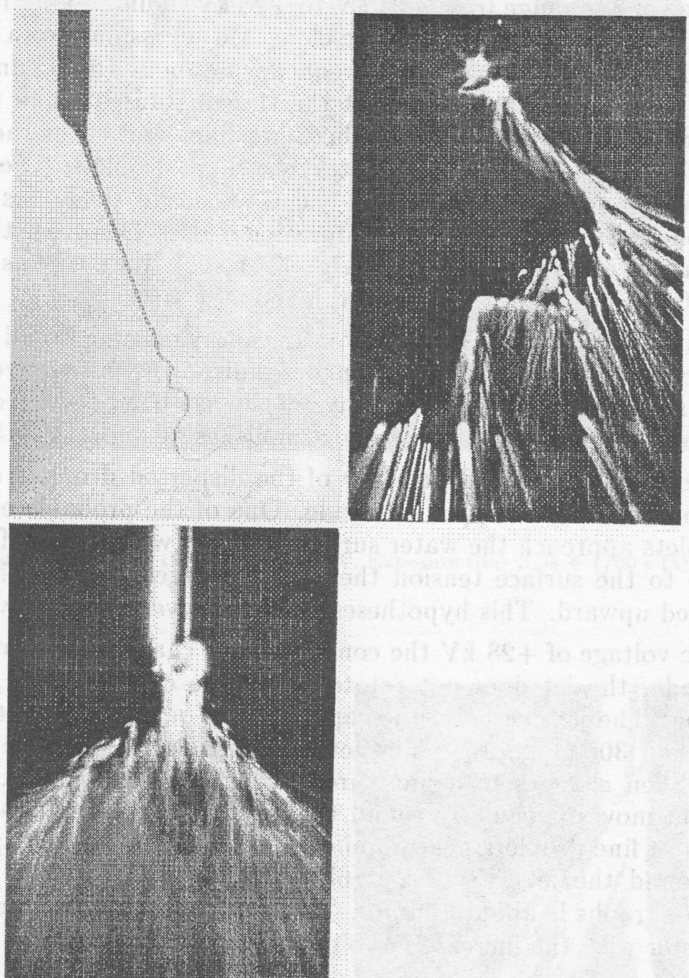
Above the voltage of +28 kV the cone-jet mode changes its form. Unlike the spiral sub-mode, the jet does not rotate round the capillary axis, but takes a stable position. The jet can lie in the capillary axis or can form with it an angle not greater than 30° (Fig. 16). The jet is straight on a distance up to about 10 mm, and then changes to a fine thread which undergoes kink instabilities, i.e. the thread moves irregularly round the mother-jet axis. The thread breaks up into series of fine droplets nearly uniform in size. The aerosol spreads nearly uniformly around the jet axis (Fig. 16b). The diameter of the jet evaluated from the photographs is about 100 μm. The jet diameter is lower and its lenght becomes shorter with the increase in voltage.

The droplet diameters are in the range of about 30 μm. It is believed that the droplets smaller than measured are also present in the sprayed aerosol, but it was not possible to estabilish this fact because of lack of an appropriate particle size analyzer.

In this sub-mode of spraying a hysteresis is also observed. The cone-jet spraying mode commences at about +28 kV, but returns back to the spiral sub-mode at +27 kV. This mode prolongates up to about +32 kV when the breakdown occurs.

In Fig. 17 the droplet modal diameter D_{mod} as a function of voltage is presented. The solid line refers to the modal diameter, while with the dashed lines the bandwidth FWHM is indicated.

a) b)



c)

Fig. 15. Liquid spraying at the voltage +26 kV. Exposure time 3 μs (a), exposure time 1/30 s (b), exposure time 1.5 ms (c).

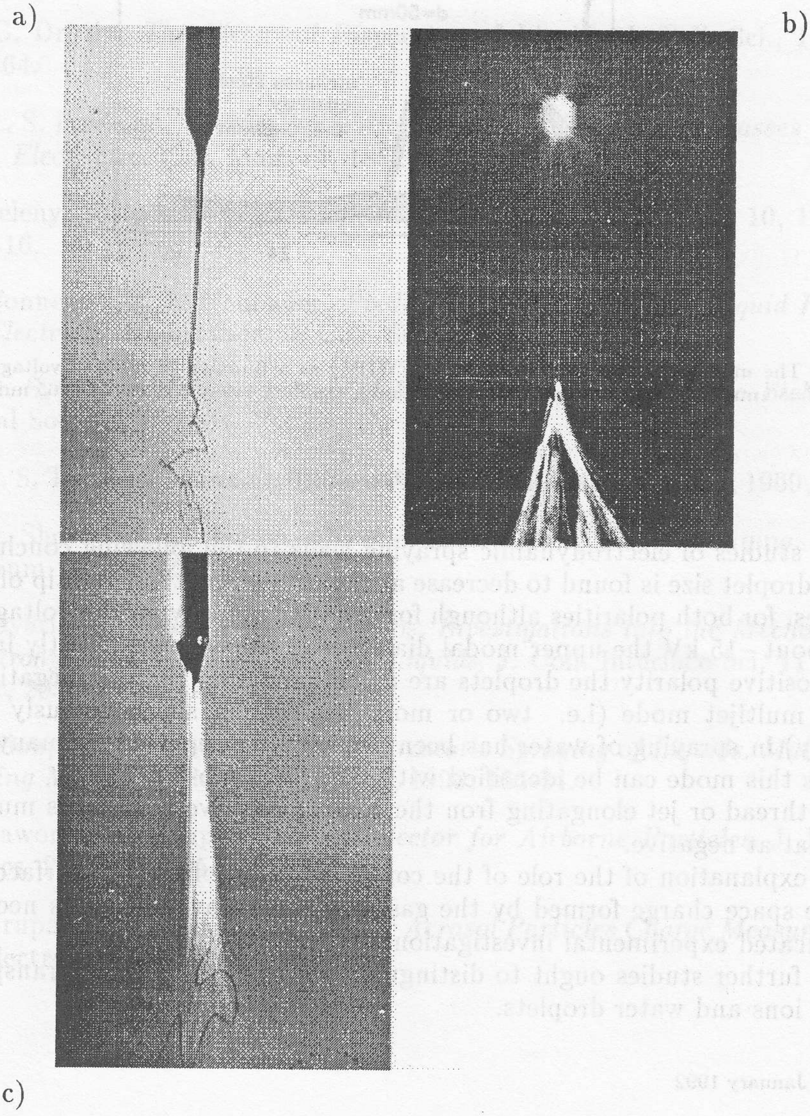


Fig. 16. Liquid spraying at the voltage +28 kV. Exposure time 3 μs (a), exposure time 1/30 s+3 μs (b), exposure time 1.5 μs (c).

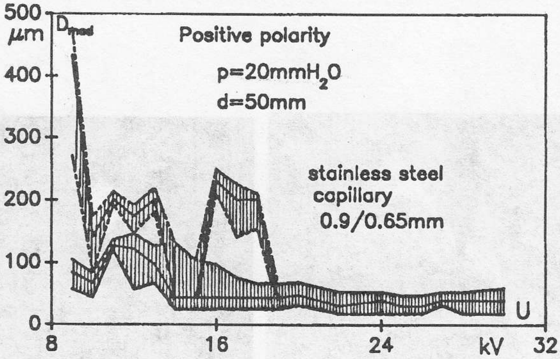


Fig. 17. The modal diameter and bandwidth (FWHM) as a function of positive voltage (electrode distance d=50 mm, capillary external diameter 0.9 mm, capillary internal diameter 0.65 mm).

5. Conclusion

The studies of electrodynamic spraying leads to the following conclusions:
1. The droplet size is found to decrease as the field strength at the tip of capillary increases, for both polarities although for negative polarity, at the voltages higher than about −15 kV the upper modal diameter of the droplets slightly increases.
2. At positive polarity the droplets are much finer than those at negative.
3. No multijet mode (i.e. two or more jets issuing simultaneously from the capillary) in spraying of water has been observed, as reported by many authors. Perhaps this mode can be identified with the spiral sub-mode.
4. The thread or jet elongating fron the cone at positive polarity is much longer than that at negative.
5. The explanation of the role of the corona discharge from the surface of water and the space charge formed by the gas ions and sprayed droplets need further sophisticated experimental investigations.
6. The further studies ought to distinguish between the current transported by the gas ions and water droplets.

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Studia morfologiczne elektrodynamicznego rozpylania wody

Streszczenie

Rozpylanie elektrodynamiczne cieczy zachodzi pod wpływem sił elektrycznych wywieranych na powierzchnię cieczy. W pracy przedstawiono wyniki badań procesu rozpadu powierzchni cieczy i opisano występujące mody rozpylania. Jako cieczy testowej użyto wody destylowanej. Ciecz wypływa przez kapilarę stalową podłączoną do źródła wysokiego napięcia prądu stałego. Prowadzone obserwacje mikroskopowe ujawniły szereg charakterystycznych modów rozpylania nie opisywanych dotychczas w literaturze.

Научные морфологические работы электродинамического распыливания воды

Резюме

Электродинамическое распыливание жидкости происходит под влиянием электрических сил вызываемых на поверхность воды. В статьє представлен результат испытаний процесса распада поверхности жидкости и описаны выступающие моды распыливания. Как мерную жидкость применено дистиллированную воду. Жидкость вытекает через стальной капилляр подсоединенный к источнику высокого напряжения постоянного тока. Выпоняемые микроскоповые наблюдения показали на ряд характеристических модов распыливания не описываемых до настоящего времени литературой.