Note on the break-up of a charged liquid jet

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The disintegration of a charged liquid jet is examined, and the break-up mechanism inferred from photographic evidence. Gravitational, molecular and electrical forces all contribute to the segmentation of the jet and determine the drop size distribution. The disintegration process is investigated from the point of view of drop generation. The segmentation of the charged jet differs from the known ways in which an uncharged jet is broken into drops.

Introduction

In most practical drop generators, the drops are produced by some mechanism which parcels out small drops from a source liquid. Regardless of how the drops are dispensed by the generator, it is quite probable that nearly all drops bear a net charge of one sign or the other. The available evidence suggests that the dispensing mechanism is responsible for the acquisition of a free charge by the drop, even when there is no net charge in the source liquid. This phenomenon is generally attributed to a simple induction process or some form of electrical double layer which is separated by a mechanical shock.

In laboratory drop-generators, electrical forces arising from the transported charge are relatively unimportant in the drop production process. Gravitational, molecular and centrifugal forces are generally utilized in dispensing drops, but several reports describe generation processes in which the drops are separated from the source liquid by electrical forces. Vonnegut & Neubauer (1952) investigated the electrical charge as a factor in the production of monodisperse liquid particles by applying potentials of 5 to 10 kV to liquids in small capillaries. Lane & Green (1956) discuss this method of drop production and show a plume of charged water droplets issuing from a tip of diameter 0·22 mm. These reports deal with the detachment of droplets from the end of a finely drawn-out capillary tube. The outward pressure due to a concentration of charge at the tip of the jet as it issues from the tube is responsible for the detachment of very small masses of reasonably uniform size. Drozin (1955) examined the electrical dispersion of liquids as aerosols, and evaluated the dispersibility of liquids in terms of such physical properties as specific conductivity, dipole moment and refractive index. Earlier reports, by such investigators as Zeleny (1914, 1915, 1920, 1935), were concerned with the discharge from liquid points rather than the production of droplets as such. These experiments all deal with surface instability due to opposing molecular and electrical forces at a curved liquid-gas interface. The criterion for such an instability at a spherical surface was established by Lord

Rayleigh (1882), and the instability of a charged cylindrical column of liquid was investigated theoretically by Basset (1894).

The disintegration of an uncharged liquid jet has received the attention of investigators since the latter part of the nineteenth century. The dynamic theory of the instability and the subsequent break-up of a long cylindrical column under the action of surface tension has been given by Rayleigh (1892). He concluded that instability results if the wavelength of a rotationally symmetric disturbance exceeds the circumference of the cylinder. The results were reached by neglecting the effects of the field fluid, but later investigators considered the characteristics of the ambient fluid as factors in the break-up of the cylinder. Haenlein (1933) shows no less than six distinct types of disintegration, and Richardson (1954) shows photographs of three break-up mechanisms.

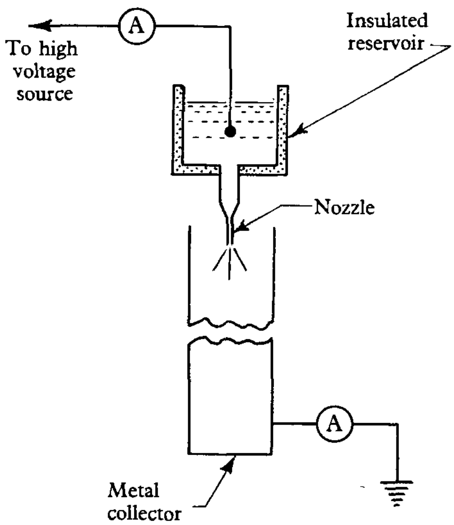

FIGURE 1. Schematic diagram of the simple apparatus for the production of charged drops.

Basset (1894) examined the effect of an electrical charge as a factor in the break-up of a liquid jet relative to the velocity, viscosity and surface tension of the liquid and the pertinent characteristics of the continuous medium. From his theoretical considerations of a straight cylindrical jet, Basset concludes that the electrical charge tends to produce stability or instability depending on whether the ratio of the circumference of the cylinder to the wavelength of an axially symmetrical disturbance is less or greater than 0·6.

Experimental technique

Charged cylindrical streams of water bearing net electrical charges were produced with the simplest of apparatus. Basically, the apparatus is nothing more than a high-voltage source with one terminal connected to ground through an ammeter, and the other connected to an electrode immersed in the source liquid. The water contained in an insulated reservoir, to which is attached a discharge tube, completes the electrical circuit. The apparatus is shown schematically in figure 1. For rates of flow necessary to produce an unbroken jet at least 1 cm below the nozzle of the discharge tube, a Wimshurst electrostatic generator was employed as a high voltage source and was found sufficient to deliver currents up to 50 μA against the circuit resistance. Charge densities corresponding to 20 μA or more and rates of flow greater than 0·1 $cm^3 sec^{-1}$ were found necessary to observe the mechanism by which the stream disintegrated due to the transported electrical charge.

Disintegration of the stream

Figures 2, 3, and 4 indicate the effects of the transported charge on the disintegration of the stream for a constant flow through the nozzle. In these photographs, water issued from a nozzle 0·03 cm in diameter at a constant rate of 0·5 cm^3 sec^{-1} and carried electrical charges at rates varying from 0 to 50 μA.

Figures 2(*a*) and (*b*) indicate the disintegration of a stream according to the theories of Rayleigh (1892) and Basset (1894). For the same nozzle diameter and rate of flow, surface charges corresponding to electrical currents greater than 12 or 15 μA result in a break-up mechanism not observed for the smaller transported charges. The main stream is drawn into a series of long thin filaments as indicated in figures 2(*c*) and (*d*). The formation and segmentation of these filaments follow no pattern observed for uncharged streams. Assuming other factors to be negligible, the geometry of the tapered filaments depends on the relative strengths of the molecular and electrical forces. The unbroken jet will be drawn into thin filaments providing the electrical effects are greater than those attributable to surface tension, but are not great enough to rupture the surface of the jet. Many drops resulting from the break-up of the filaments are less than 25 μ in diameter and leave the formation point with considerable energies.

The long tapered filaments are formed as a result of the surface energy component arising from the presence of the electrical charge. From a consideration of minimum surface energy, the molecular forces tend to decrease the surface to volume ratio, whereas the energy component due to electrical charges is minimized by increasing this ratio. Figures 2(*c*) and (*d*) indicate the manner in which the stream disintegrates by a vigorous whipping action. The attempt to minimize the surface energy takes the form of a sudden increase of the surface area. The area increase takes the form of violent sidewise displacements of segments of the stream. Large looping filaments are formed on alternate sides of the stream axis. Segments of the stream may be displaced until the length of the loop is about twenty times the original length of the displaced segment. Each elongated filament separates at the point of maximum displacement resulting in a series of nearly horizontal filaments tapered towards either end.

The process of loop and filament formation allows little in the way of quantitative treatment, but calculations of surface charge densities relative to the geometry of the disintegrating stream suggest a possible mechanism. During the disengagement of a large drop, an asymmetry in the connecting filament results in a net force in the direction of greatest convexity. This force is due to the presence of surface charge and is responsible for the initial sideways displace-

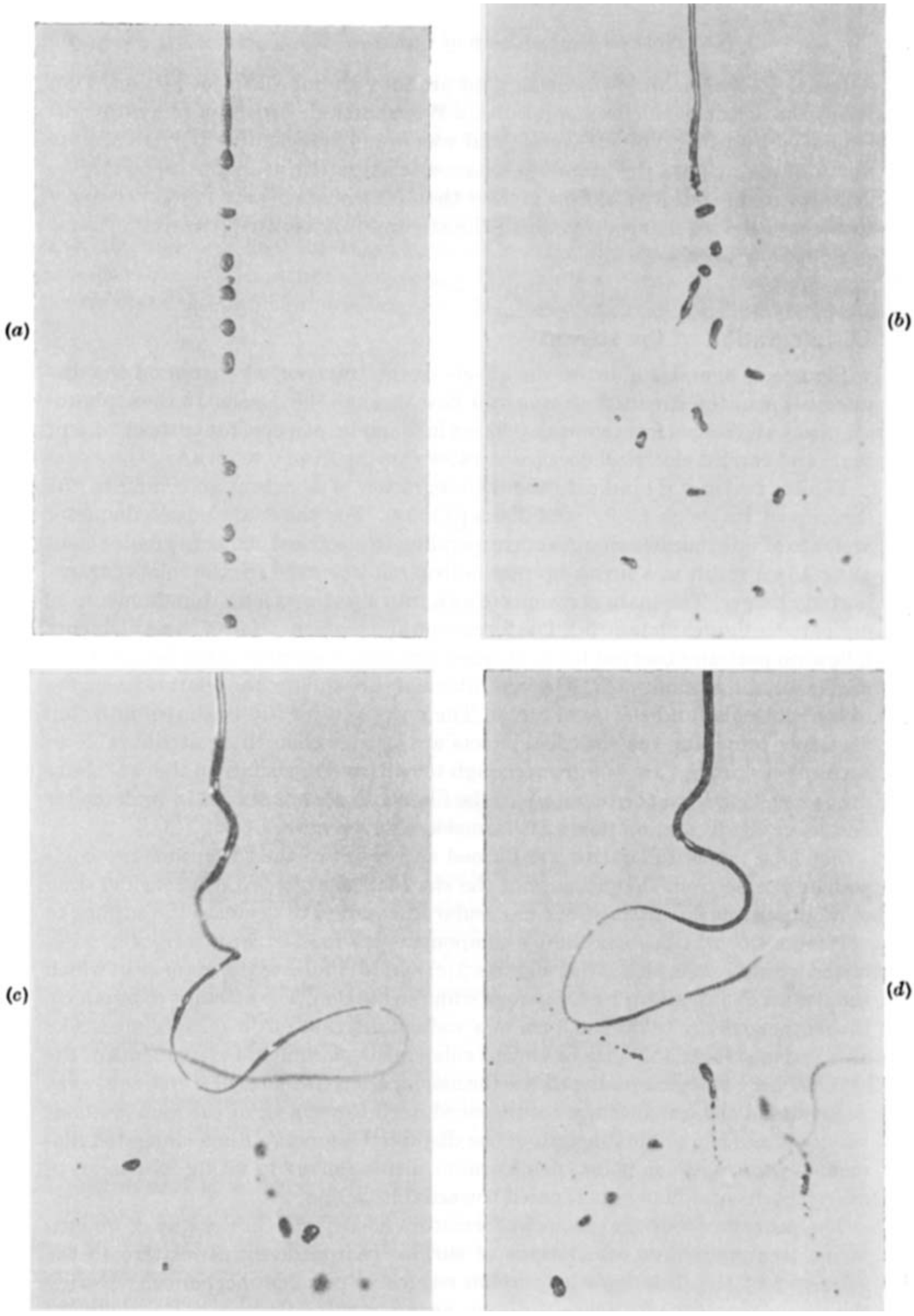

FIGURE 2. (*a*) Photograph of an uncharged stream of water issuing from a nozzle at the rate of 0·5 g sec^{-1}. (*b*) The same stream carrying a current of 10 μA. (*c*) The same stream carrying a current of 20 μA causes the stream to have a whipping motion. (*d*) The same stream carrying a current of 30 μA.

ment, which, in turn, tends to increase the accelerating force by concentrating the charge on the convex side of the loop. The cumulative effect creates the loop in a matter of 0·3 sec for rates of flow of 0·5 cm sec^{-1} and electrical currents

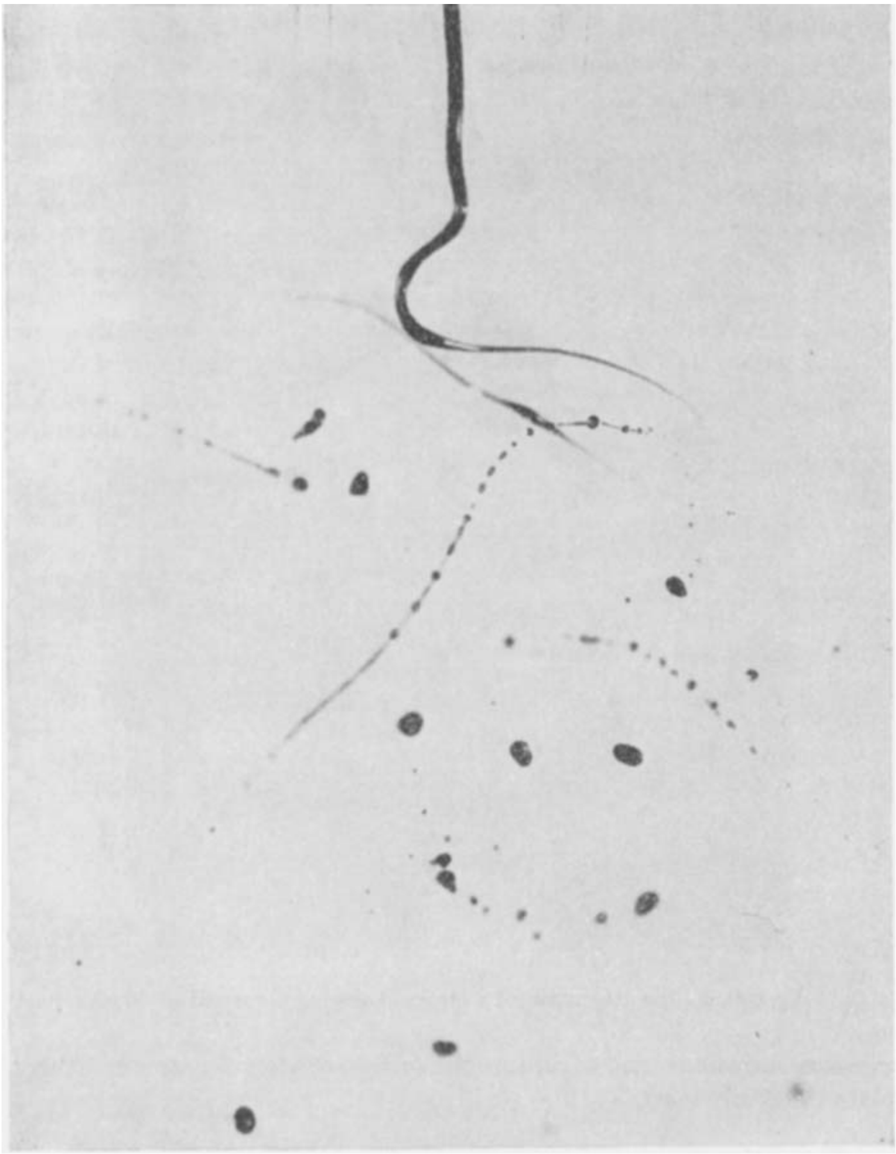

FIGURE 3. Whipping motion of stream carrying a current of 40 μA. Drops of intermediate size are in evidence.

greater than 12 or 15 μA. The creation of one loop initiates the action which creates a second, which is generally in the same plane, but on the opposite side of the vertical line of flow. The whipping action depends on the size of the stream and the rate as which the charge is being transported. For larger streams and greater currents the geometry is less regular and the process less violent. High surface

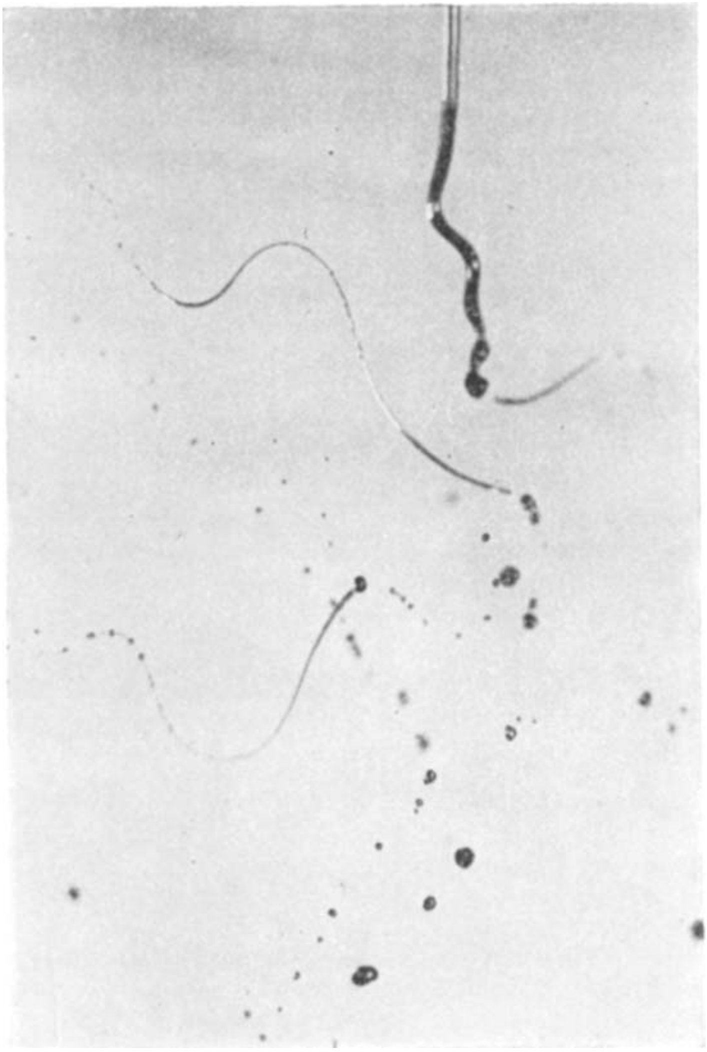

FIGURE 4. Disintegration of a stream carrying a current of 50 μA.

charge concentrations tend to rupture the surface of a heavier stream rather than displace the entire mass.

Drop formation

The large drops of figures 2 (*a*) and (*b*) are formed by the break-up of the main jet due to the action of gravitational and molecular forces. The mechanism has been well understood for many years. The secondary drops, commonly called Plateau's spherules, are in evidence in both photographs.

The fragmentation of the tapered filaments results in drops of sizes not observed for streams issuing from a nozzle under the force of gravity. A group of droplets ranging in size from less than 5 to about 25 μ in diameter leave the formation point at relatively high velocities in directions such that 60 % are within 30° of the horizontal. This angular distribution lends support to the hypothesis that the smaller droplets are pinched from the ends of the nearly horizonal filaments. The uniformity of drop size which results from formation at the tip of a finely drawn capillary tube is lacking when drops are ejected from the end of an unconfined filament. The more massive centre of the tapered filaments is the source of most of the drops of intermediate size. Figures 3 and 4 show drops of intermediate size formed by the break-up of the filaments.

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