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INSTABILITY OF ELECTRIFIED LIQUID SURFACES.

BY JOHN ZELENY.

IN a recent paper[1] a brief description was given of the appearance of a liquid surface undergoing disintegration owing to instability arising from an electric charge.

The observations recorded were made in connection with some experiments on the electric discharge from liquid surfaces and the work was confined to eye observations, through a microscope, of the surface in question when this was illuminated by the light of a spark from a Leyden jar. Some of the phenomena appeared to be of sufficient interest to warrant the making of a more accurate record of them by the aid of photography, and a few results obtained by this method are described in this paper.

The apparatus used for getting the electrified surface was similar to that used previously and for details reference is made to the paper mentioned. Briefly, the apparatus consisted of a vertical glass tube, 0.92 mm. in diameter, joined from its upper enlarged end by rubber tubing to a reservoir of the liquid. A drop of liquid at the lower end of the small glass tube was the part under observation. The liquid was charged to several thousand volts from a static machine, and a grounded plate was placed about 2 cm. below the end of the glass tube. Ethyl alcohol was used for nearly all of the experiments inasmuch as water is not a convenient liquid for showing some of the phenomena, because, owing to its high surface tension, the potential at which instability of its surface is first obtained in air at atmospheric pressure is nearly the same as that at which an electric discharge begins.

2. The source of light mostly employed in taking instantaneous pictures of the liquid was a condenser discharge between magnesium electrodes in air. For some of the exposures the spark was passed through mercury

[1] Proc. Camb. Philos. Soc., 18, p. 71, 1915.

vapor at atmospheric pressure in an arrangement similar to that described by C. T. R. Wilson.[1]

An induction coil was used for charging the Leyden jars, and this was provided with a rotary, mercury-jet interrupter which could be operated successfully up to 800 interruptions per second for taking moving pictures of the phenomena studied. In taking such pictures an image of the drop was focused on a vertical slot in the center of a long board placed about 2 meters from the object. A photographic film was placed in a slide on the far side of this board, and this slide, propelled by strong rubber bands, was shot past the opening in the board at a speed that carried it a distance equal to the width of the opening in the time between two interruptions. For these pictures transmitted light and the magnesium electrodes were used exclusively.

3. Some of the photographs which were taken are reproduced in Plate I. The magnification is not the same for all of the pictures but it can be estimated in each case from the diameter of the glass tube which was 0.92 mm. throughout. The liquid used was alcohol except for the case represented by Fig. 7. No luminosity accompanied any of the phenomena shown so that the so-called point discharge was not present and all transfer of electricity from the charged surface was effected by means of droplets of liquid and none by gaseous ions.

Two series of pictures taken in the manner described in § 2 are shown in Figs. 1 and 2, the time interval between the separate exposures being approximately one eight-hundredth of a second. The pictures are to be followed from right to left as the downward motion of the flying drops indicates. The doubling of some of the pictures is due to irregularity in the action of the illuminating spark. In the experiment represented by Fig. 1, the alcohol was charged to 5,000 volts and the liquid in the reservoir was 3 cm. above the end of the glass tube, while for Fig. 2 the corresponding numbers were 6,000 volts and 4 cms.

4. A few general statements may help to make clear what is going on in these pictures. Suppose the liquid unelectrified and the supply reservoir raised until liquid issues from the end of the tube at a certain slow rate. Drops with a diameter larger than that of the tube will form, break off and fall away. On electrifying the liquid sufficiently and lowering the reservoir to keep the outflow of liquid the same as before, the drops will be drawn out into more or less cylindrical form before they break from the tube. After severance these cylindrical pieces will coalesce into drops whose diameter may be considerably smaller than that of the glass tube from which they came.

[1] Proc. Roy. Soc. London, 87, p. 279, 1912.

When however the electrification is increased to a point where the electric force at the surface of the liquid attains a certain limiting value, which depends upon the surface tension of the liquid and the radius of curvature of its surface, then, irrespective of whether or not the liquid pressure is sufficient to force liquid out of the tube, the surface becomes unstable and any slight accidental displacement of the surface results in a rapid increase of that displacement. This condition is first reached at the lower end of the drop where the electric density is greatest. What happens is that the liquid at this place is pulled out into a fine thread, which eventually breaks up into minute drops.

5. Returning now to Figs. 1 and 2, it will be seen that very fine points of liquid appear on some of the drops at the end of the tube and also on some of the detached masses. These are the places where there is surface instability, although the fine threads of liquid spoken of can hardly be made out and the myriads of small droplets forming from them are quite invisible.

The fact that instability is confined to but one very small area of the surface is to be explained by the redistribution of electric charge caused by the liquid drawn out from the first place that breaks down. It is possible, however, by increasing the voltage of the surface to have a number of these places of instability existing at the same time on a surface of the dimensions used in these experiments.

As already explained the emission of the large drops seen in the figures is not an accompaniment of surface instability but is conditioned by the excessive pressure of the liquid in the tube. This pressure may be removed by lowering the supply reservoir and then the surface of the drop on the tube appears quite stationary with one or more of the fine points of liquid coming quite abruptly out of the surface where instability obtains. It is noted that the elongated detached masses of liquid retain the instability points for a short time only after they are separated from the tube above. The numerous droplets formed at the points soon carry away enough electric charge to reduce the surface to stable conditions, after which each mass of liquid quickly collapses into a spherical drop. The rapidity with which this collapse takes place is well illustrated by the first two pictures on the left in Fig. 1. In the second picture the elongated cylinder still carries the pointed end while in the first picture, only one eight-hundredth of a second later, the whole has collapsed into a nearly spherical form.

The shielding effect of the drops explains a common behavior illustrated by the pictures in Fig. 1, where it is seen that the drops fly alternately to one side and the other side of the vertical.

The electric force acting on some of the fine threads of liquid often undergoes very rapid changes in direction on account of the drops of liquid in front. Thus in the lower part of the sixth picture in Fig. 2 the fine thread appears as a large double loop, owing to the shielding effect of a drop just off the picture. Smaller but more complex loops are seen in some of the other pictures as for example in the third picture of Fig. 1. Again, the two successive pictures of Fig. 8 show a complete reversal of field. Fig. 3 shows a case where the liquid was torn into shreds by forces varying rapidly in direction. A number of the pieces are barely visible, being out of focus. The appearance at the end of the cylinder in Fig. 4 is that of clouds of finely divided material.

6. Under certain conditions of potential and hydrostatic pressure it is possible to get the alcohol drop at the end of the tube to assume the form of a cone with a fine thread of liquid coming from its apex. This condition is quite steady and is especially suited for a closer study of the liquid thread, which characterizes the state of instability, as well as of the droplets into which the thread disintegrates. The general appearance of this stage is shown in Fig. 5 which represents a picture taken after an exposure of 30 seconds with light concentrated upon the object from an arc lamp placed at the side. The potential of the drop was 5,000 volts.

The thread or stem of liquid coming from the apex of the cone actually had a much smaller diameter than the picture shows since it was not perfectly stationary during the exposure. Measurements of the thread with a microscope showed its diameter to be approximately 0.004 mm. Combining this value with a measurement of the rate of emission of the liquid it was found that the thread was pulled out at the rate of about 8 meters per second. The liquid thread remains intact for but a short distance in this case, breaking up into drops rather suddenly at the place where the enlargement shows in the picture. This enlargement is not apparent however in eye observations with a microscope, the drops flaring out gradually from the solid stem.

The spreading of the drops formed from the central thread of liquid into a more or less conical volume is most probably due to the combined action of the divergence in the electric field and of the mutual repulsion of the drops. No evidence has been obtained of any still finer threads coming from the end of the thread visible in the picture.

The line of demarcation seen in the brushlike cloud of drops shows these to be of two different sets. The outside portion is presumably made up of the set of comparatively small drops which form between the main drops whenever any liquid jet breaks up into drops. None of

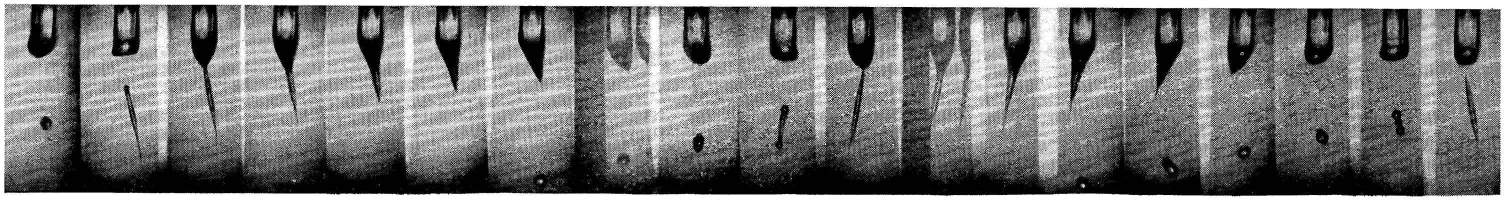

Fig. 1.

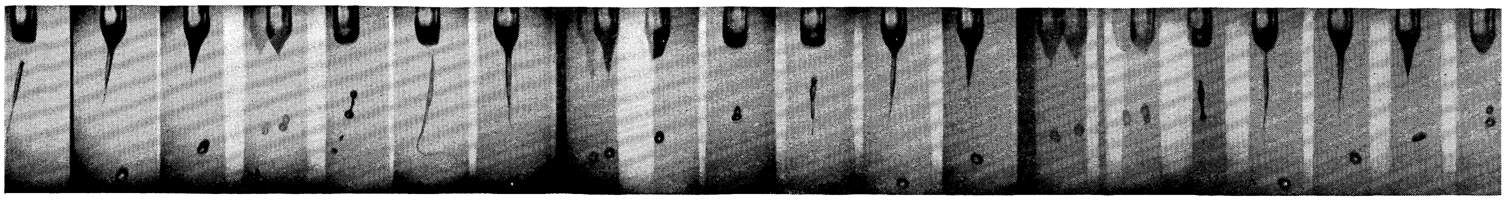

Fig. 2.

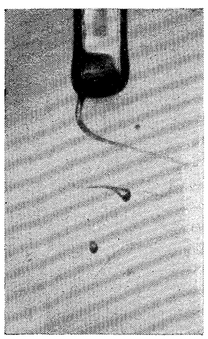

Fig. 3.

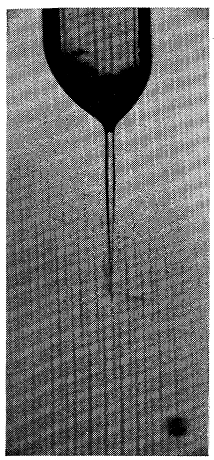

Fig. 4.

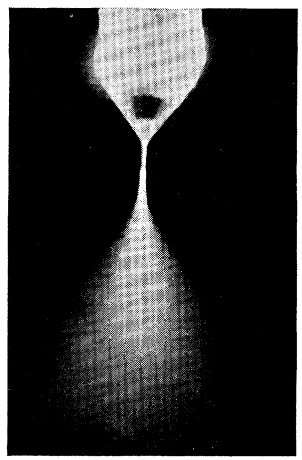

Fig. 5.

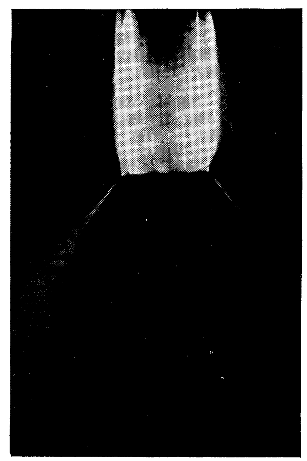

Fig. 6.

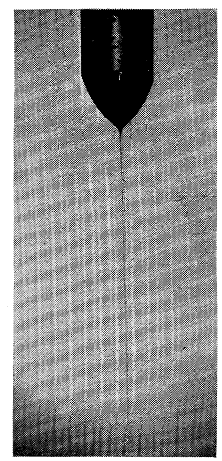

Fig. 7.

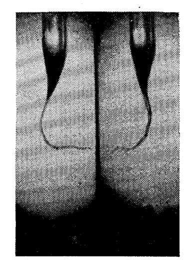

Fig. 8.

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the individual drops could be seen in flight with a microscope in instantaneous light, but high powers could not be used owing to their short working distances. Rapid evaporation doubtless made futile the attempts which were made to observe them after catching them on some solid surface. The measurements given above show that even if a length of thread equal to twice its diameter went into the making of each drop, the number of these drops formed per second would be a million.

It may be remarked that the brush spray appears colored both by transmitted light and by reflected light, the colors persisting in each case when the eye is within about 45° of the direction of the light. The colors depend not only on this angle of sight but differ also for the different portion of the brush, indicating thus a difference between the sizes of the drops at these parts.

It should be added that when the condition represented by Figs. 1 and 2 is viewed in continuous light it too has the appearance of a more or less compact brush, like that in Fig. 5, although the outline is not so sharp and the appearance is somewhat granular.

7. On reducing the hydrostatic pressure below the value which was requisite for maintaining the single central spray shown in Fig. 5, the cone of liquid flattens into a drop and the thread of liquid now issues from the side of this drop. Under these conditions of pressure it is possible by increasing the voltage to obtain two points of instability on the surface where two jets of liquid with their sprays of drops come from the surface, as shown in Fig. 6, which is again a time exposure by side illumination. By increasing the voltage still further eight or more such stationary jets may be obtained at the same time, the jets being all arranged on the outer edge of the drop.

8. Glycerine was used in some of the experiments because its viscosity is so much greater than that of alcohol. When the conditions were arranged for a single thread coming from a steady surface it was found that the thread was pulled out in this case a distance of 15 mm. before it underwent disintegration into drops. The set of large drops flared out in their flight into a fan similar to that obtained with alcohol (Fig. 5) but the small drops all shot out from one place in directions at right angles to the axis of the thread and the sharp outer boundary of their paths formed a paraboloid of revolution about this axis. The phenomenon was not sufficiently stationary to permit a successful time exposure to be taken by reflected light, but Fig. 7 shows a picture taken with a 2.5 seconds' exposure by transmitted light of a part of the thread coming from the drop of glycerine. The potential used was 7,000 volts. The diameter of this thread was approximately 0.007 mm. and the speed with

which it was pulled from the drop was about 3 meters per second. The diameter of the drops was found by catching them in various ways and measuring them under a microscope. The large drops in the central brush differed considerably in size but had an average diameter of about 0.01 mm., and the diameter of the small ones in the outer flare was approximately one quarter of this value.

The long known experiment of threads being pulled from highly electrified molten sealing wax is doubtless an example of the action described in this paper.

I am greatly indebted to the skill of my assistant, Mr. W. B. Lang, for the success of the pictures.

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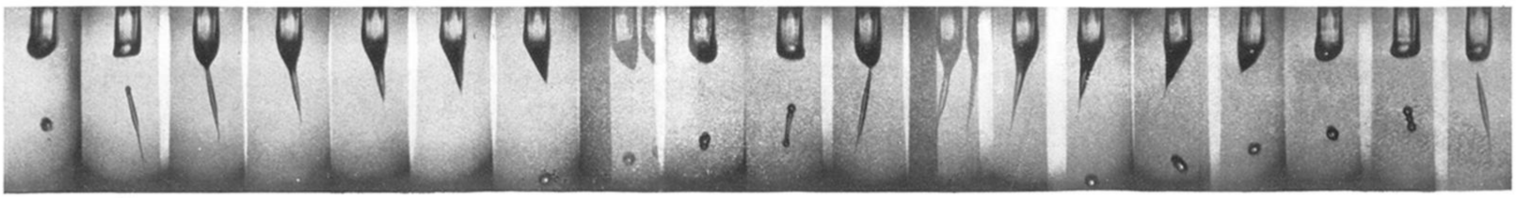

Fig. 1.

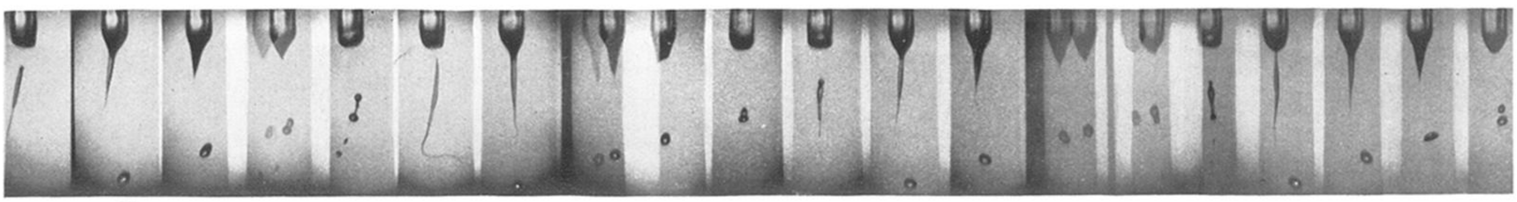

Fig. 2.

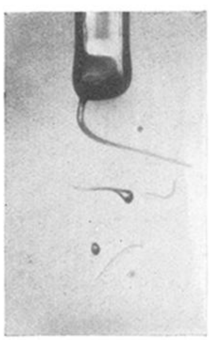

Fig. 3.

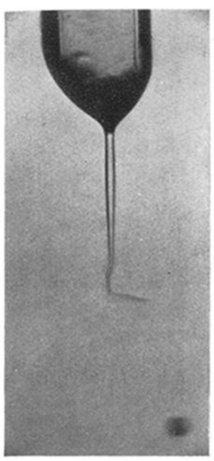

Fig. 4.

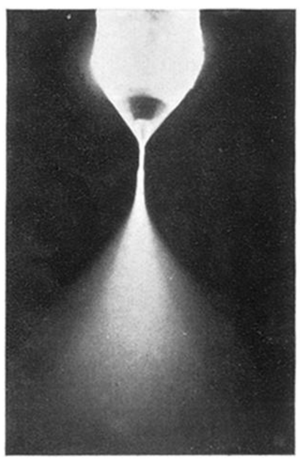

Fig. 5.

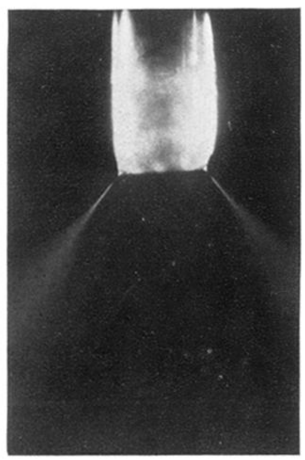

Fig. 6.

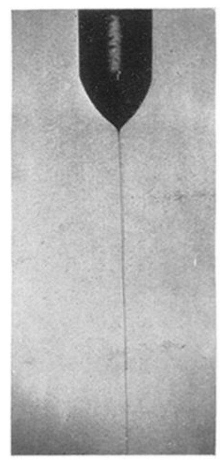

Fig. 7.

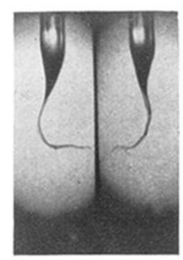

Fig. 8.