MECHANISM OF A CONDENSED SPARK DISCHARGE.

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Considerable work has been done recently on the electric spark discharge by the engineering profession with a view of eliminating corona discharges and of devising adequate protection against steep wave-front impulse discharges.

Perhaps the most noteworthy results to be obtained along these lines is the work of McEachron and Wade,[1] who were the first to report successful instantaneous oscillographs of condensed electric discharges of frequencies as high as 20,000 kilocycles and at potential differences of approximately 100 kilovolts. The oscillographs showed that the first oscillation of these powerful discharges was approximately rectangular in shape and contained by far the greater part of the energy in the wave-train, the main transient of which usually attained its maximum value in about 0.4 microseconds.

Another interesting report along similar lines is Bulletin No. 19 of the Engineering Experimental Station, Purdue University, entitled "A Photographic Study of High Voltage Discharges." This bulletin is a second progress report on the investigation of the electrical fixation of atmospheric nitrogen and represents the results of several methods of attack used to determine the mechanism and characteristics of the corona discharge.

Other interesting publications on the more general properties of the spark discharge have also appeared. Several of these latter reports are rather closely related to the engineering aspect of the problem. One, the work of Anderson[2] on electrically exploded wires, shows that the energy dissipated within the spark interval of about 10 microseconds is approximately 30 calories, which expended into a mass of 2 mgs. should have raised its temperature to about 300,000 degrees centigrade but based upon the intrinsic temperature corresponded to about 20,000 degrees centigrade. Using a ballistic pendulum arrangement, Anderson determined the pressure produced by his spark discharge as being approximately 40 atmospheres.

Another study of the latter type was a report by the writer[3] on "The Shadowgraph Method as Applied to a Study of the Electric Spark," in which instantaneous photographs were obtained for various disposi-

* The investigation on which this article is based was made in the Physics Laboratory of Indiana University under the direction of Dr. A. L. Foley, to whom the writer is indebted for his assistance and counsel throughout the experiment.

[1] General Electric Review 28, 622, 1925.

[2] Astrophys. Jour. 51, 37, 1920.

[3] Dissertation: "The Shadowgraph Method as Applied to a Study of the Electric Spark," executed at Indiana University, 1926; Phil. Mag. 32, 1098, 1928, abstract in Phys. Rev. 29, 752, 1927.

"Proc. Ind. Acad. Sci., vol. 37, 1927 (1928)."

tions of capacity and inductance. It is upon the results of this work substantiated by such reports as have just been mentioned that the proposed theory of a condensed electric discharge contained herein is developed.

Theory of the Condensed Electric Discharge. M. Toepler[4] showed that an electric discharge between a point and a plane frequently commences with a dark discharge and ends with an arc, providing the potential difference is sufficiently increased and maintained. A graphic representation of Toepler's spark discharge appears in figure 1. Here the abscissas represent current and the ordinates represent potential difference.

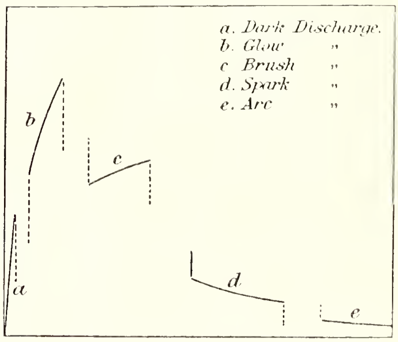

Fig. 1—A graphic representation of Toepler's spark discharge.

The following theory, however, is based upon the behavior at atmospheric pressure of a normal condensed discharge between points. If one will include the mechanical phenomena occurring in such a discharge, the sequence of the various stages of the discharge will be: (a) dark discharge; (b) glow discharge; (c) brush discharge; (d) spark discharge; (e) sound pulse; (f) striations; and (g) gases and vapors. The writer will consider each of these separately.

(a) Dark Discharge. Due to the increasing electric field set up between the terminals of a spark gap connected to a charging condenser, it would seem logical to believe that all charged air particles due to "natural ionization," and coming under the influence of the increasing field, should be gradually drained to their respective poles. This movement of charged bodies whose momentum is constantly increasing constitutes the dark discharge. Faraday[5] discovered its existence from the increased lag which an electric discharge exhibits when a magnet is brought in the vicinity of a gap region through which such a discharge is taking place. Nipher[6] likens a dark discharge to the trans-

[4] Ann. d. Phys. 7, 477, 1902.

[5] Faraday: "Experimental Researches," No. 1417; No. 1544.

[6] Nipher: "Experimental Studies in Electricity and Magnetism," Blakiston, (Philadelphia) 1914, p. 5.

portation of negative corpuscles across the gap space by supercharged molecules.

(b) Glow Discharge. A stage is eventually reached when in addition to the charged particles flowing from various points in the gap region and uniting in "drainage" channels as they proceed to their respective poles, a glow discharge takes place in the form of electrons ejected from the negative terminal. The glow may, however, be twofold, a negative and a positive glow, the former due to the combining effect of electrons ejected from the negative terminal with positive ions; the latter to the deliverance of electrons to the positive terminal from adjacent air molecules. Thus, one would expect a greater luminescence at the positive than at the negative terminal because the electrons being lighter and having a shorter distance to travel, exist in greater abundance about the positive terminal than do the derived positive ions about the negative terminal. Nipher[7] suggests that the scintillations frequently visible at the positive terminal of a glow discharge are the beginnings of the drainage streamers of a brush discharge.

(c) Brush Discharge. Let us now conceive of individual air molecules as being polarized by the action of the electric field and arranging themselves in narrow chain-like aggregations, like smoke and dust do under similar circumstances. These aggregations being bodies of high specific inductive capacity will act on the field like pointed conductors, with a consequent concentration of electric lines of force on the ends of the chain so that the maximum electric force will be considerably greater than the average force which we ordinarily measure.

Simultaneous with the above we should by this time expect ionization by collision on the part of the more rapidly moving ions. Thus it is mainly due to these two agencies that the brush discharge takes on its form. Faraday[8] found that when two equal spheres discharge their electricity by a brush discharge into air, the discharge occurs at a lower potential for the negative ball than for the positive; meaning that more electricity accumulates on the positive ball than on the negative before the occurrence of the discharge. Thus when the positive discharge does take place it is finer than the negative.

(d) Spark Discharge. If the brush discharge is sufficiently abrupt, it will blend with the initial or pilot spark of the principal series of electrical oscillations known as the main spark discharge. For it is the brush discharge, preceding the initial discharge and burning its way along a molecular thread of charged air and dust particles of considerable resistance, which develops the required amount of heat necessary for spontaneous ionization of the air in the gap region. The disruption of the air by the initial discharge gives rise to a sound pulse which travels but a few millimeters during the entire life of the spark and which is accompanied by considerable pressure. The heat developed by the initial discharge volatilizes some of the electrode metal, with the result that subsequent oscillations take place in the vapor of the metal which seemingly diffuses into the gap region under forced pressure.

[7] Nipher: loc. cit. (6) p. 7.

[8] Faraday: loc. cit. (5) No. 1501.

With certain dispositions of apparatus, globules or molecular aggregations are literally projected from the electrodes into the gap space, while under other conditions the discharge may terminate in a bright glow at each terminal.

This procedure was first observed by Trowbridge,[9] who made photographic studies of the spark discharge by means of a rotating mirror. It was further corroborated by Schuster and Hemsalech,[10] who photographed the spectrum of the spark by means of a rotating mirror device and found that the initial discharge consisted of air lines while the

Fig. 2—Vapor is diffusing under forced pressure into gap space.

main electrical oscillations consisted of vapor lines. Figure 2 exemplifies the case where a gradual diffusion of the vapor takes place into the gap space; figure 3 represents the condition where the vapor is projected into the gap space in the form of globules and molecular aggregations; and figure 4 represents the case where a discharge terminates in a glow.

Fig. 3—Vapor being projected in form of globules and molecular aggregations.

(e) Sound Pulse. The origin of the sound pulse, which is a compression wave, has already been indicated under the preceding discussion. It has its inception with the striking across of the pilot spark, the latter being a consummation of the total brush discharge. It is

[9] Phil. Mag. 36, 343, 1893.
[10] Proc. Roy. Soc. 64, 331, 1899.

then that the air in the gap region is subjected to an enormous strain due to the tremendous heat which is suddenly developed. The layers of air coming under the influence of this heat expand in an exceedingly brief space of time and leave the core of the tube which extends across the gap space in an evacuated condition. Thus as the jerk of a whip as it cuts the air produces a vacuum and the rebound of the air as it fills the vacuum creates a sound disturbance, so the tube of hot rarefied gas gives birth to a sound pulse. The sound pulse, however, being a mechanical phenomenon, will not mature until the electrical oscillations have decayed.

This phase of the electrical spark already received considerable attention shown by the work of A. Toepler,[11] Mach,[12] Wood,[13] M. Toepler,[14] and Foley.[15] The photographs by the writer show very plainly that the

Fig. 4—Discharge terminates in glow at positive terminal.

velocity of the sound pulse exceeds the rate of dissipation of the hot gases. An interesting sound pulse appears herewith. Figure 5 represents a heavy discharge. Based upon Professor Foley's[16] work on "Instantaneous Velocities of Spark Waves," the latter spark is about 35 microseconds old; furthermore, this spark also enables us to estimate the period of exposure of these shadowgraphs as being of the order of 3 microseconds.

(f) Striations. With the dissipation of the electrical energy due to heat developed in the metallic circuit and the spark gap; to insulation losses of the condenser and of the remainder of the circuit; to brush leakage of the condenser; to eddy currents induced by the alternating magnetic field; and, to electromagnetic radiations, the tube of hot gas and vapor extending between the gap terminals and serving as the carrier of the electric oscillations now extinct, will become singularly affected by laminal aggregations of supercharged particles which are urged away from or attracted to oppositely charged terminals without

[11] Pogg. Ann. 131, 33, 1867.
[12] Sitz. d. Wien Akad. 98, 1333, 1889.
[13] Phil. Mag. 48, 218, 1899; 50, 148, 1900.
[14] Ann. d. Phys. 41, 838, 1904; 27, 1043, 1908.
[15] Phys. Rev. 35, 374, 1912.
[16] Phys. Rev. 16, 449, 1920.

an appreciable interchange of charge. Since we know that a negative and a positive region can exist adjacent to one another, for example, the dark and luminous columns of a discharge tube, the conjecture might be made that the carriers are returning to regions of more stable equilibrium after having delivered all of their supercharge and perhaps a part of their normal charge. Hence these alternately dark and luminous regions may under the proper conditions exist as striations which can quite properly be interpreted as electrically produced sound waves of very short wave lengths.

Thus, M. Toepler[17] found that the discharge of an induction coil through the flame of a candle gives a bright discharge traversed by dark spaces. Earlier, A. Toepler[18] in a stroboscopic investigation of the air produced by the passage of the electric spark found regions of

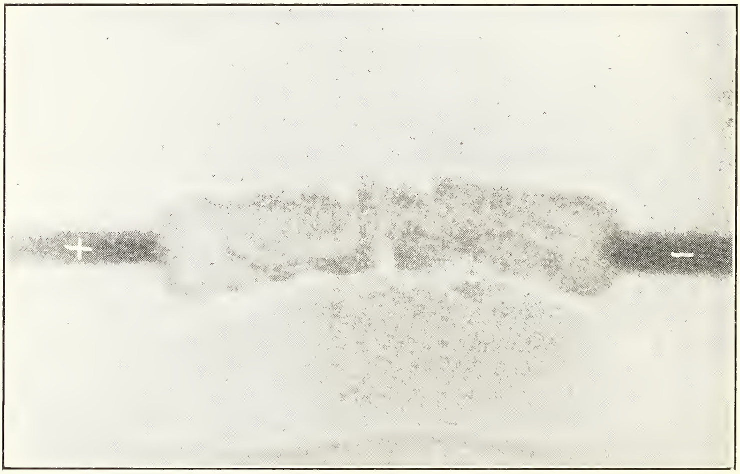

Fig. 5—Sound pulse resulting from a heavy discharge.

periodic swellings and contractions as if the centers of greatest disturbance were distributed at regular and finite intervals along the line of discharge. It remained, however, for Paalzow[19] to discover the necessary conditions for the appearance of striations. He found by discharging a Leyden jar through a vacuum tube that whenever the resistance of the discharge circuit was less than a certain critical value, the image of the spark was seen as a series of separated bars of light and the discharge tube showed by the identity in the appearance of the glow light at the two terminals that the discharge was bi-directional. Hence it would appear that with the expulsion of the sound wave, the gap region exists in a state of low pressure; and, if the pressure is

[17] Wied. Ann. 63, 109, 1897.
[18] Pogg. Ann. 134, 194, 1868.
[19] Pogg. Ann. 112, 567, 1860; 118, 178, 1861.

sufficiently low and the resistance of the gap circuit less than the critical value referred to above, striations will result. Nipher[20] explains the existence of striae in the positive column of the Geissler tube as being electrically produced air waves, the adjoining halves of which are Faraday dark spaces and conducting columns. Figure 6 shows a rather ancient striated spark known as the "caterpillar type," due to a weak

[20]Nipher: loc. cit. (6) p. 47.

Fig. 6—Striations in an ancient spark due to a weak discharge.

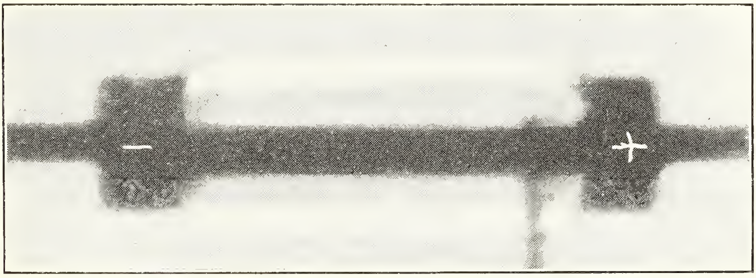

Fig. 7—Clearly defined striations of millimeter widths due to a strong discharge.

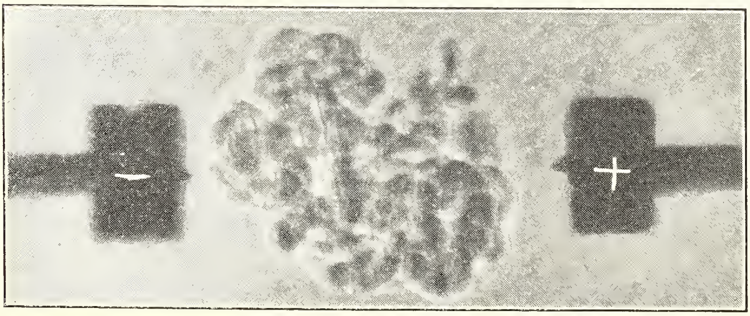

Fig. 8—Regular diffusion of gases and vapors in a normal discharge after all electrical and other mechanical phenomena have subsided.

discharge; while figure 7 represents a strong discharge and shows clearly defined striations of approximately 1 mm. widths.

(g) Gases and Vapors. With the emergence of the sound pulse, the cessation of the striation-vibrations and the readjustment of the air pressure in the gap space, the hot gas in this region tends to fulfil one of the fundamental properties of all gases, namely, diffusion. A peculiarity of the mode of diffusion as exhibited by figure 8 is the momentum acquired by these columns or tubes of hot gases and vapors.