THE PRESSURE INCREASE IN THE CORONA.

BY EARLE H. WARNER.

I. INTRODUCTION.

IT has been reported by Farwell and Kunz that at the instant the corona appears about an axial wire in a cylindrical tube, the pressure of the gas in the tube suddenly increases.[1] It has always been stated that this pressure increase could not be due to heat, because of the instantaneous character of its appearance, and because of the rapidity with which it disappears as soon as the potential is removed from the wire. Since the only theories which have been advanced to explain the corona assume it to be an ionization phenomenon, it seemed reasonable to suppose that this pressure increase was due to the increase in the number of gas particles in the tube, and so it was called ionization pressure. Experiments have been performed and reported[2] which show that this pressure increase is exactly proportional to the corona current, with the wire positive when dry air, hydrogen, nitrogen, carbon dioxide, oxygen and ammonia are the gases in the tube. Since the publication of this data Arnold[3] has contended that the pressure increase could be completely accounted for as the result of Joule's heat, and that the assumption that it is due to ionization is untenable. To support this contention Arnold performed experiments " by electrically heating the central wire in apparatus similar to Farwell's and " observed the pressure increase. With such an apparatus Arnold attempted to show (1) that an increase in pressure due to heat appears suddenly, (2) that for a given power consumed in the tube the increase in pressure due to heat is of about " the same magnitude as those observed " in the corona.

In order to show clearly that the pressure increase is not due to heat a series of comparative experiments were performed with the pressure increase caused, first, by producing the corona glow on the wire and, second, by heating the central wire. The pressure increase observed in the first set of experiments will be referred to as *caused by corona* and in the second set as *caused by heat.*

[1] Dr. S. P. Farwell, "The Corona Produced by Continuous Potentials," Proc. A. I. E. E. Nov., 1914. Dr. Jakob Kunz, "On the Initial Condition of the Corona Discharge," PHYS. REV., July, 1916.

[2] Earle H. Warner, "Determination of the Laws Relating Ionization Pressure to the Current in the Corona of Constant Potentials," PHYS. REV., Sept., 1916.

[3] H. D. Arnold, (Abstract) PHYS. REV., Jan., 1917.

A few computations have also been made which strengthen the results of the experiments.

II. EXPERIMENTAL RESULTS.

1. The reason why one who sees this pressure increase, as recorded by a quick-acting pressure meter, thinks it is not a heat effect, is because of rapidity with which it appears and disappears. Arnold showed that the pressure increase occurred quite rapidly when caused by heat. The following curves show the difference in the rapidity of appearance and disappearance of the pressure increase caused by heat, and caused by corona. It will be noticed in Fig. 1, where the pressure increase was caused by heating the central wire, that fifteen seconds was required for the prssure to come to its maximum value, and that from the time the current was broken twenty-five seconds was required for the pressure to return to practically its original value, while in Fig. 2, where the pressure increase was caused by corona, only three seconds was required for the maximum pressure to be attained and that the pressure came back to practically its original value in eighteen seconds. In this last case from the appearance of the phenomenon it seems, if the aneroid pressure meter had less inertia, that the pressure increase could be determined in less than three seconds. These curves show that the pressure increase appears five times as rapidly when caused by corona as when caused by heat, and disappears also more rapidly.

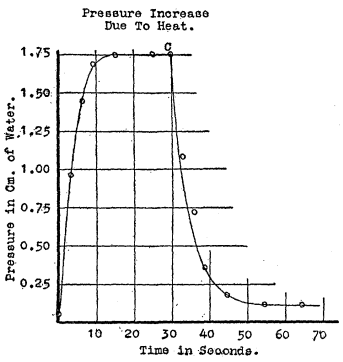

Fig. 1.

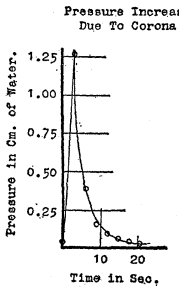

Fig. 2.

2. In the pressure increase due to corona, a short time interval of five to seven seconds occurs after the sudden increase of pressure, before the heat effect in the corona begins to be noticed. This is shown by an abrupt bend, A, in the curve where the pressure increase is plotted against time, as is done in Fig. 3. No such bend occurs in the case where the pressure increase is caused by heat alone, as is shown in Fig. 1. In the work which has previously been reported the pressure increase measurements were always taken at the point A, and this seems to be practically independent of the heat effect.

3. The heat which is produced in the corona discharge, shown by the gradual pressure increase from B to C, Fig. 3, is distributed throughout the whole volume of enclosed air and so, when the current is broken does not radiate rapidly because the air is a poor conductor. This is shown very clearly in Fig. 4. This seems to show that the pressure increase due to

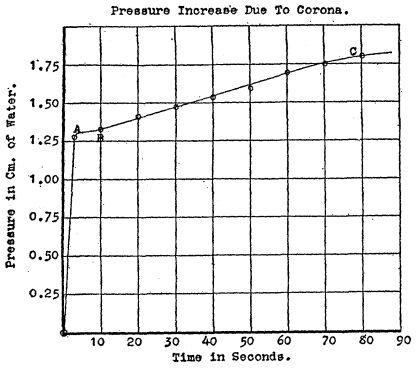

Fig. 3.

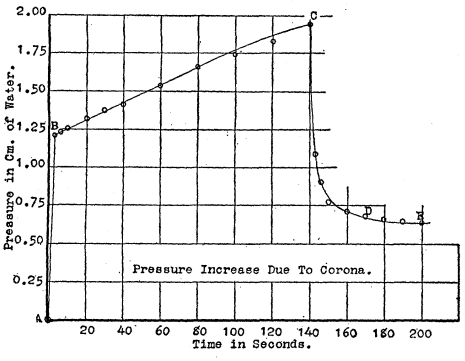

Fig. 4.

heat in the corona is represented by the difference of ordinates of C and B (Fig. 4). As soon as the corona current is broken at C the increase in pressure due to corona at once disappears, but the increase in pressure due to heat in the corona discharge remains, as is shown by the difference of ordinates of D and A. This difference is always very nearly equal to the difference of ordinates of C and B. This heat energy produced by the corona current, since it is distributed through the gas, radiates very slowly, as is shown by the gradual descent of the curve from D to E. No such effect is observed when the increase of pressure is due entirely to heat, as is shown in Fig. 1. This curve (Fig. 1) shows that twenty-five seconds after the current through the wire is broken at C the resultant pressure increase due to heat has practically disappeared; while Fig. 4 shows that twenty-five seconds after the corona is removed from the wire the increase in pressure due to the corona has disappeared, but practically all the pressure increase due to heat in the corona (ordinates C minus B approximately equals ordinates D minus A) still remains and radiates very slowly.

4. If the increase in pressure is due to heat, the same increase in pressure should result when the same power is consumed (*a*) with a corona current through the gas, (*b*) with a heating current through the wire. Figs. 5 and 6 show that this is not the case. The powers consumed in the two cases are not exactly the same, but one can see that were they the same, the increase in pressure due to corona would be approxi-

mately one half the increase in pressure due to heat. The power in the case of the corona was obtained by multiplying the potential difference between the wire and the tube by the corona current, and in the case of

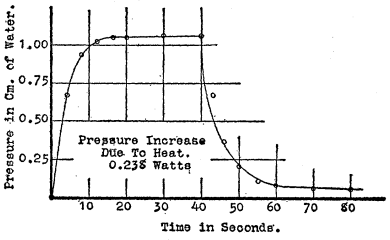

Fig. 5.

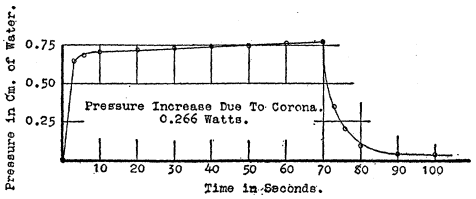

Fig. 6.

the heated wire was obtained by multiplying the current through the wire by the potential difference across that portion of the wire which was in the tube.

5. If the increase in pressure in the corona discharge is due to heat the temperature of the air in the corona tube must increase. This may or may not be the case in the luminous layer near the wire but the temperature of the gas in the tube at a point four millimeters from the wire actually decreases. This was determined by inserting a sensitive thermocouple made of very fine Copper-Advance wire into the corona tube. The temperature decreased only at the instant the corona appeared. In a short time, after the heat due to the corona began to appear (corresponding to the slope B to C, Figs. 3 and 4) the temperature of the gas in the tube began to increase. This cooling effect is shown in Fig. 7. Comparing Figs. 7 and 3 it is seen that the increase in pressure which was measured at A was observed while there was an actual cooling in the corona tube. This cooling should be expected when air or oxygen are in the tube, for under these conditions ozone is formed. Since the formation of ozone from oxygen is always accompanied with an absorption of heat the temperature of the air or oxygen would tend to lower. Mr. J. W. Davis, working on corona about hot wires in hydrogen, has discovered that the appearance of the corona about a tungsten wire heated to white heat, causes it to cool to dull red. This tends to show that even in the corona glow itself there is a cooling effect.

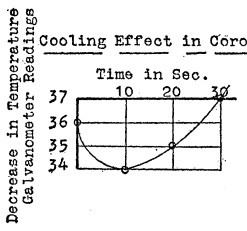

Fig. 7.

6. If the increase in pressure in the corona is due to heat one should expect it to be the same with the wire either positive or negative. As has been previously mentioned it is impossible to obtain measurements

when the wire is negative because of the presence of beads. The negative corona is entirely different from the positive corona.

7. The following consideration will further show that the increase in pressure can not be due to heat. The heat produced by the corona current will be given by the equation $H = 0.238\ eit$ and, if the observed pressure increase is due to heat, the increase in pressure Δp will be proportional to the heat, and we can write $\Delta p = k\ eit$. Now the only way for Δp to vary directly as i, the corona current, as is the case—shown by curves in the last article—is for e to be independent of i. Data shows that this is not the case.

III. RESULTS FROM THEORETICAL CONSIDERATIONS.

1. If the increase in pressure is due to heat it is possible to compute the magnitude of the pressure increase when one knows the watts of electrical energy consumed in the tube. The trial represented in Fig. 6 gives us this data. The observed pressure increase was measured in three seconds so that the total number of joules of work consumed by the tube in that time was $3 \times 0.266 = 0.798$ joules and this corresponds to 0.1909 calories. Knowing the volume of the tube, the temperature and pressure of the air in it, the mass of the air in the tube can be computed. With the above-mentioned quantity of heat and mass of air, together with the specific heat of the air at constant volume, the temperature rise of the air can be computed, assuming that the electrical energy is converted into heat. This temperature rise comes out to be 2.44° C., which at constant volume corresponds to a pressure increase of about nine cm. of water, while the observed pressure increase in this particular trial amounts to about seven tenths cm. of water. In this computation radiation and conduction losses have been neglected because they would be very small from a body 2.44° C. above room temperature. This shows that the observed results lie in a different order of magnitude from what would be expected if Arnold's theory were true.

2. Arnold states, if "we compute the corona currents that would result from the presence of enough ionized particles to produce the observed pressure changes, the currents calculated are many thousand times greater than those actually obtained." Such a statement is only true when the ionized particles are produced in a uniform or practically uniform electric field. This is not the case in the corona tube. H. T. Booth is publishing data on the distortion of the field in the corona tube. This data shows that the potential gradient near the wire is very high—of the order of 30,000 volts per cm. This is the arcing gradient, in which it is probable every molecule is ionized. Then for a long space between the

wire and the tube there is a very small gradient. With this condition of the field, near the wire every molecule may be ionized and still the resultant current be very small, for few of the ionized particles near the wire will pass through the space where there is a small gradient. Simple computations based on kinetic theory show that the maximum observed pressure increases can be explained by ionization if every molecule of the air within 1.39 mm. of the wire is ionized. Within this distance the potential gradient is equal to the arcing gradient and therefore probable that all molecules are ionized.

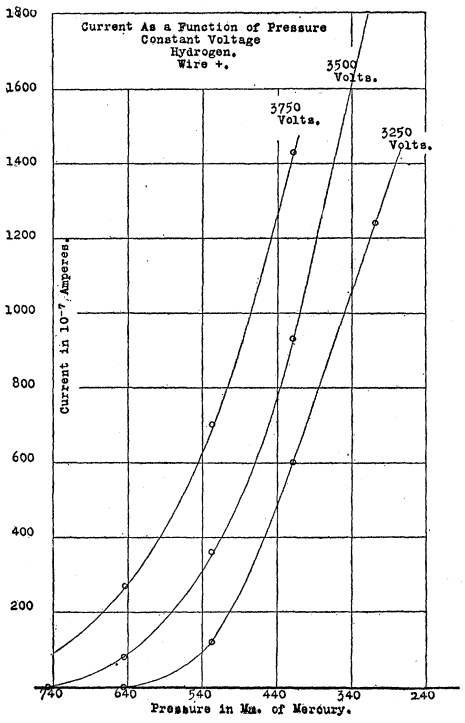

Fig. 8.

IV. Further Verification of Kunz's Theory.

The final equation as presented in the last article is

$$ki = \frac{v_0}{e}(p_1 - p_0) + \text{a constant},$$

where i is the corona current, v_0 the volume of the tube, e the potential difference between the wire and the tube, $p_1 - p_0$ the pressure increase, k a constant and p_0 the initial pressure. This equation shows that for a constant potential difference e, the current i should increase as p_0 is lowered. Data were taken, by measuring the current at various measured pressures, caused by a constant potential difference, which verifies this theory. These data are shown graphically in Figs. 8 and 9 when pure hydrogen and nitrogen respectively were the gases in the tube.

V. Summary and Conclusions.

Experimental results show:

1. That the increase in pressure due to corona appears and disappears much more rapidly than when due simply to heat.

2. That the heat in the corona discharge is not a prominent factor until many seconds after the corona appears.

3. That in equal energy experiments the increase in pressure due to corona differs from the increase in pressure due to heat by about 50 per cent.

4. That at the instant the corona appears the gas in the tube at a small distance from the wire is cooled.

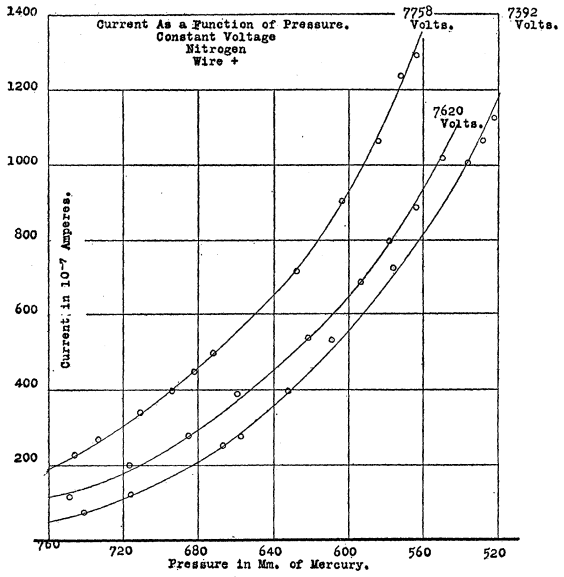

Fig. 9.

5. That the theory advanced by Kunz is verified in one more field, namely in the relation between current and pressure for constant voltage.

These results together with conclusions drawn from simple calculations, force one to believe that the pressure increase in the corona discharge is not due to Joule's heat. With the recent knowledge of the distortion of the field in the corona tube it seems very possible that the increase in pressure is due to ionization.

The writer desires to express his appreciation to Professor A. P. Carman for the use of the laboratory facilities, and to Dr. Jakob Kunz for his continued interest and suggestions.

LABORATORY OF PHYSICS,
UNIVERSITY OF ILLINOIS,
June, 1917.