

DISTRIBUTION OF POTENTIAL IN A CORONA TUBE.

BY HARRY T. BOOTH.

I. INTRODUCTION.

1. *General Characteristics of D.-C. Corona.*—The name corona has been applied collectively to the conduction phenomena appearing when a sufficiently high potential difference is applied to two electrodes (two parallel wires, or two coaxial cylinders) separated by a gas. Corona appears for both alternating and direct impressed potential differences; for the purpose of our investigation, however, direct current corona was the more suitable.

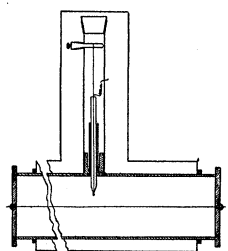


Fig. a.

Since a knowledge of the distribution of potential between the electrodes will be necessary for any fundamental corona theory, an investigation has been carried out at this laboratory to determine the field at every point between a wire and a coaxial tube, under various conditions of impressed voltage, pressure, size of wire, and current. It is hoped that the data taken will aid in the formulation of an adequate corona theory.

II. METHOD.

The distribution of potential between a wire and a coaxial cylinder was investigated in the following manner.

A hole was drilled in the side of a cylinder, and an insulated wire terminating in a bare spherical tip was arranged so that it could be moved radially between the wire and the tube. A micrometer microscope directed on a fixed point of the movable wire served to determine the relative position of the point. An electrostatic voltmeter of small capacity was connected in series with the exploring point and the tube.

When the point was moved to any portion of the radial field, the voltmeter quickly showed a constant deflection, indicating that the potential of the point was in equilibrium with that of the field at that particular place.

By moving the exploring point from the tube to the wire, observing the voltmeter readings at certain intervals, a comparatively accurate estimate of the intensity of the field was obtained.

III. APPARATUS.

1. *The Corona Tube.*—The corona tube as indicated in the accompanying sketch was 35.5 cm. long and 7 cm. in diameter. The central wire was of copper, well polished, and stretched tightly. In all, four wires were used, No. 40, No. 32, No. 28 and No. 20 B. & S. gauge.

The ends of the tube were covered with heavy plate glass, drilled for the central wire, and sealed fast with half and half wax.

Since it was necessary to work at pressures lower than atmospheric, a glass tube was sealed over the exploring rod, so arranged with ground joints and springs as to allow the point to be moved at will without destroying the constant pressure.

2. *Source of Potential.*—The source of continuous potentials used in this set of investigations consisted of a battery of 40 500 volt, 0.5 ampere, shunt-wound, D.-C. generators connected in series.

These were arranged so that the potential could be varied continuously from about 300 volts up to 20,000 volts. Power for the driving motors was supplied by a motor generator set equipped with a voltage regulator, so that the voltage variation on the 110-volt power line was constant to within less than .5 per cent.

In general, the potential of the high tension line was as constant as the accuracy of the work demanded.

3. *Voltmeters.*—For the measurement of voltages, three voltmeters were used, a Kelvin electrostatic voltmeter with three ranges, a Braun electrostatic voltmeter, and a General Electric electrometer type voltmeter.

These instruments were calibrated with an attracted disc electrometer, equipped with a scale and vernier so that the distance between plates could be read to 0.05 mm. The force on the disc was measured by a fine balance.

The Braun voltmeter had a range of 0–3,500 volts, and since it is essentially an electroscope, it was almost ideal for use with an exploring point.

The Kelvin instrument had 3 ranges, 0–5000, 2,000–10,000, and 4,000–20,000 volts.

4. *Current Measurements.*—Currents between the wire and the tube were measured by means of a D'Arsonval galvanometer, used in connection with an Ayrton universal shunt. The figure of merit of the galvanometer was obtained, using standard resistances and a dry cell whose E.M.F. had been determined by comparison with a standard cell.

TABLE OF CURVES.

Figure.	Curve.	Wire B & S Gauge.	Voltage.	I Amperes.	P Mm. of Hg.	Temp. °C.	Remarks.
1	1	20	12,500	$9.76 \cdot 10^{-6}$	745	25°	Faint glow
	2	20	13,850	$6.62 \cdot 10^{-6}$	745	25°	Good glow
	3	20	15,420	$1.6 \cdot 10^{-4}$	745	25°	Good glow
	4	20	16,000	$1.78 \cdot 10^{-4}$	745	25°	Good glow
2	1	20	1,450	$3.9 \cdot 10^{-6}$	23.5	27°	Dull glow
	2	20	2,150	$2.31 \cdot 10^{-4}$	23.5	27°	Bright glow
	3	20	2,950	$5.58 \cdot 10^{-4}$	23.5	27°	Brilliant purple glow
	4	20	2,150	Electrostatic curve			
3	1	20	10,000	$9.23 \cdot 10^{-6}$	450	27°	3 or 4 steady beads wire negative
4	1	28	8,400	$3.19 \cdot 10^{-6}$	745	25°	No apparent glow
	2	28	10,200	$2.66 \cdot 10^{-6}$	745	25°	Faint glow
	3	28	11,500	$7.1 \cdot 10^{-6}$	745	25°	Dull glow
	4	28	13,450	$1.95 \cdot 10^{-4}$	745	25°	Good glow
	5	28	14,000	$3.73 \cdot 10^{-4}$	745	25°	Bright glow
5	1	28	1,520	$4.43 \cdot 10^{-6}$	19	24°	Good glow
	2	28	1,750	$1.35 \cdot 10^{-4}$	19	24°	Good glow
	3	28	2,320	$3.73 \cdot 10^{-4}$	19	24°	Bright glow
	4	28	2,890	$6.92 \cdot 10^{-4}$	19	24°	Brilliant glow
	5	28	2,320	Electrostatic curve			
6	1	28	1,800	$9.48 \cdot 10^{-4}$	19	24°	About 30 steady beads
7	1	32	6,510	$4.17 \cdot 10^{-8}$	747	25°	No glow
	2	32	6,825	$1.91 \cdot 10^{-6}$	747	26°	Distinct glow
	3	32	7,425	$1.91 \cdot 10^{-6}$	747	26°	Good glow
	4	32	8,400	$5.94 \cdot 10^{-6}$	747	26°	Good glow
	5	32	9,900	$9.54 \cdot 10^{-6}$	747	26°	Bright glow
8	1	32	6,825	$1.91 \cdot 10^{-6}$	747	26°	Distinct glow
	2	32	6,825	$2.03 \cdot 10^{-4}$	241	24°	Bright glow
	3	32	6,825	$3.46 \cdot 10^{-4}$	885	24°	Brilliant glow
	4	32	6,825	Electrostatic curve			
9	1	32	5,050	$1.79 \cdot 10^{-8}$	744	26°	No glow
	2	32	5,650	$2.39 \cdot 10^{-6}$	744	26°	A few dull beads
	3	32	7,250	$3.10 \cdot 10^{-6}$	744	26°	Beads 1 cm. apart
10	1	40	4,520	$4.77 \cdot 10^{-8}$	740	22°	No glow
	2	40	4,700	$1.19 \cdot 10^{-6}$	740	22°	Distinct glow
	3	40	6,500	$2.26 \cdot 10^{-6}$	740	22°	Good glow
	4	40	8,400	$8.29 \cdot 10^{-6}$	740	22°	Good glow
	5	40	9,900	$1.67 \cdot 10^{-4}$	740	22°	Brilliant glow
	6	40	8,400	Electrostatic curve			

IV. RESULTS.

1. *General Type of Curves.*—By the method of exploration already described, curves for the distribution of potential between wire and tube were taken for No. 40, No. 32, No. 28 and No. 20 copper wires stretched along the axes of the tube. These curves were taken for various pressures and voltages after the appearance of the corona. Representative curves obtained are shown in Figs. 1 to 10, and the conditions under which each curve was taken are given in Table I.

For the No. 40 wire, it was found impossible to obtain curves of the

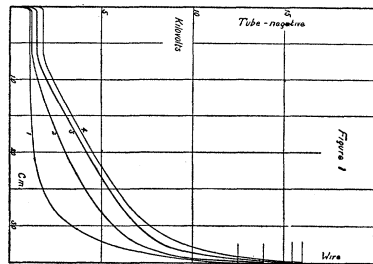


Fig. 1.

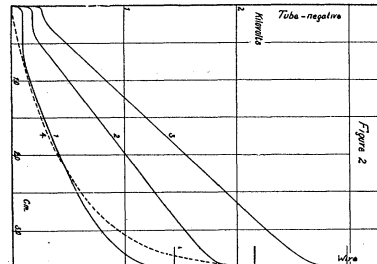


Fig. 2.

potential distribution when the wire was negative; for a given position of the exploring point the readings of the voltmeter were not constant. The beads appearing when the wire is negative were seldom at rest, and this would lead to the conclusion that each movement of the beads is accompanied by a change in the field surrounding the wire.

For No. 32 wire, when the wire was negative, two curves shown in Fig. 9

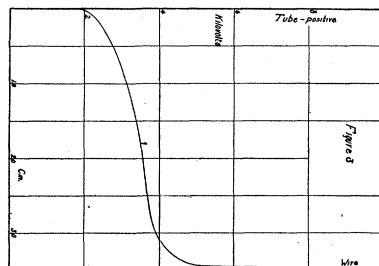


Fig. 3.

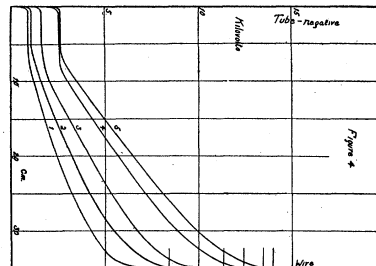


Fig. 4.

were taken before the corona appeared, also a portion of a curve for a voltage at which there was a distinct series of beads along the wire.

Curves were also obtained for No. 28 and No. 20 wire when the wires were negative, the same general characteristics being exhibited in each.

3. *Discussion of Curves.*—The corona discharge in general is divided

into two classes, according as (1) the wire is positive, and (2) the wire is negative.

The first case, when the wire is positive, is characterized by a uniform

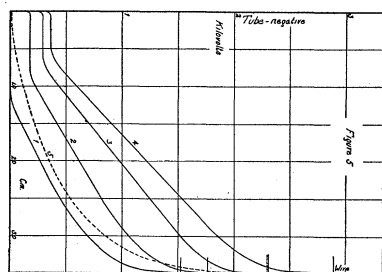


Fig. 5.

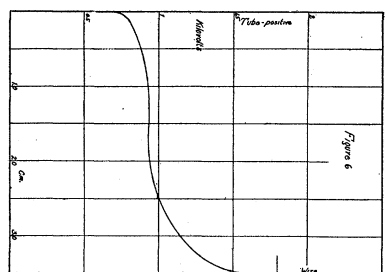


Fig. 6.

purplish glow around the wire. The second case, however, differs in appearance. When the potential is sufficiently high, small tufted beads

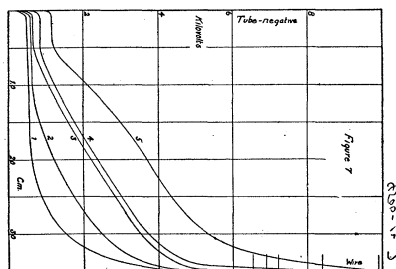


Fig. 7.

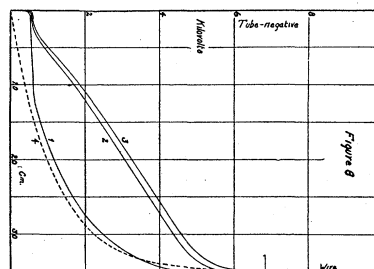


Fig. 8.

appear on the negative wire, and are at rest only under exceptional conditions.

Curves are shown for both positive and negative wires. Let us con-

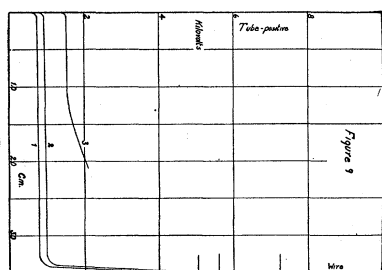


Fig. 9.

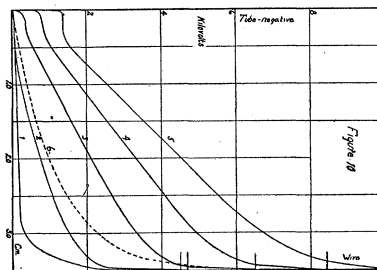


Fig. 10.

sider the appearance of the potential distribution curves when the wire is positive.

1. *The Positive Wire.*

In general, the space between the anode and the cathode may be broken up into four regions.

1. A region immediately surrounding the wire, which is characterized by a very large potential gradient. This may be due to the excess of the number of ions or electrons approaching the electrode over the number of those leaving, since the former number includes ions generated at all parts of the field, whereas the latter contain only ions that are generated in the narrow layer close to the wire. Thus we can see that the charges on the excess of negative ions near the wire disturb the electric field so that the potential difference per centimeter, or the gradient, is large near the surface of the wire.

2. A region of approximately constant force extending from the "surface layer" region adjacent to the wire, to a point which varies with the pressure, current, and voltage. At the higher voltages, the actual potential at a given point in this region is greater than the theoretical electrostatic potential, and the tangent to the curve may be either greater or less. Figs. 2 and 5 show the electrostatic curve (dotted), in comparison with actual curves taken.

3. A region of little or no force near the tube. In passing from II. to III. the number of positive ions increases (since they are generated in all the space between the wire and region III.), and their charges oppose those on the negative ions to such a degree that not only the negative charges on the ions, but also the electrostatic forces due to the configuration of the system are neutralized.

4. A region close to the tube, corresponding to the "surface layer" contiguous to the wire. In this space, positive charges accumulated at all the remaining parts of the radial field are predominant, and there is an abrupt cathode drop at the surface of the tube.

2. *Wire Negative.*

When the wire is negative and corona appears, a potential curve is obtained which differs somewhat from the positive curves. Large cathode and anode drops appear, and the intervening space has a very small field. Reasoning similar to that explaining the shape of the curves when the wire is positive explains the negative curves.

So in general, the anode and cathode drops of potential are predominant in both types of curves. There are several reasons for this, namely: .

1. Polarization potential between a metal and a gas.
2. Accumulation of ions.
3. Reflection of ions.

4. Different velocities of positive and negative ions.
5. A non-uniform field.

The Potential Curves from a Theoretical Point of View.

1. The starting point of the corona.

We have Peek's empirical formula for the starting intensity,

$$E_1 = E_0 \left(1 + \frac{\beta}{\sqrt{R_1}} \right), \quad (1)$$

where E_1 is the force at the surface of the wire of radius R_1 and E_0 and β are constants.

From the general electrostatic theory, at the moment when the corona discharge is starting, just before the field has been disturbed by the moving charges,

$$E_1 = \frac{(V_1 - V_2)}{R_1 \log \frac{R_2}{R_1}}. \quad (2)$$

Therefore at the instant when the corona starts

$$E_0 \left(1 + \frac{\beta}{\sqrt{R_1}} \right) = \frac{(V_1 - V_2)}{R_1 \log \frac{R_2}{R_1}} \quad (3)$$

or

$$E_0 = \frac{(V_1 - V_2)}{R_1 + \beta \sqrt{R_1}} \frac{1}{R_1 \log \frac{R_2}{R_1}}, \quad (4)$$

which resembles the general formula for the electric force between two concentric cylinders,

$$E = \frac{(V_1 - V_2)}{r \log \frac{R_2}{R_1}}. \quad (5)$$

Hence, when $r = R_1 + \beta \sqrt{R_1}$,

$$E = E_0.$$

2. Calculation of the volume density of electrification in the space between the two concentric cylinders.

For a system where the potential at a point is due to moving charges as well as static charges, we have Poisson's equation expressing the density in terms of the potential,

$$\nabla^2 V = -4\pi\rho, \quad (6)$$

or, writing it in cylindrical coördinates,

$$\frac{\partial^2 V}{\partial r^2} + \frac{1}{r} \frac{\partial V}{\partial r} + \frac{1}{r^2} \frac{\partial^2 V}{\partial \varphi^2} + \frac{\partial^2 V}{\partial z^2} = -4\pi\rho. \quad (7)$$

For this particular case, the derivatives in z and Φ are zero, so rewriting the above equation, using total derivatives,

$$\frac{d^2 V}{dr^2} + \frac{1}{r} \frac{dV}{dr} = -4\pi\rho. \quad (8)$$

Since the density is an undetermined function of the radius, the equation cannot be integrated directly. If, however, we plot the potential against the distance from the axis, a graphical method will aid in the determination of the density. That is, if the first derivative of the potential is determined from the curve for a series of values of r , these new values may be plotted against the radius again. By repeating this process with the derived curve, a relation between the second space derivative and the radius is obtained. From these two derived curves, then, the density may be computed according to equation (8).

Fig. 11 is a repetition of Curve 4, Fig. 1, and Fig. 12 shows the density as computed for the different values of r .

The density curve shows what we have deduced intuitively in regard

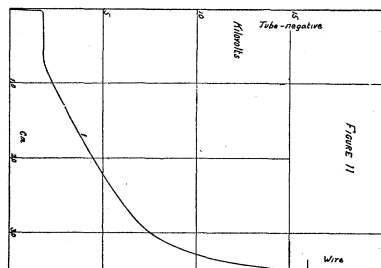


Fig. 11.

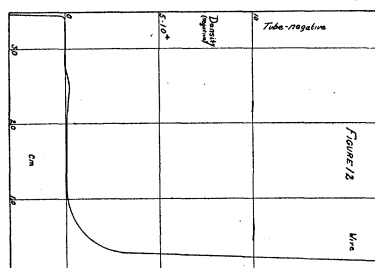


Fig. 12.

to the charges necessary to produce the observed distortion of the field. The large resultant negative charge near the positive wire and the positive charge near the negative tube should be expected. A peculiar maximum appears at about 2.7 cm. from the wire (Fig. 12).

4. Sources of Error.

1. Potential assumed by a sphere in an ionized gas.

It is difficult to draw conclusions as to the absolute potential of a sphere in a conducting gas, since it is very likely that the potential at an undisturbed point in a gas is not the same as the potential assumed by a sphere when its center is at this point.

In the case of a sphere near the positive electrode, its potential being initially the same as that of the gas, two streams of ions move in opposite directions past the side of the sphere, one containing a large number of

negative ions, and the other a smaller number of positive ions. It intercepts more negative ions than positive, so that its potential falls below that of the surrounding gas. The charge thus acquired by the sphere increases until the effect which it produces in attracting positive and repelling negative ions causes them to come in contact with the sphere in equal numbers. The final value of the potential assumed by the sphere is too high by an amount which depends upon the relative velocities of the positive and negative ions.

Conversely, when the exploring sphere is close to the negative electrode, there are a greater number of positive ions intercepted than negative ions, so that the potential of the sphere rises above the potential of the undisturbed gas, until finally an equilibrium is reached, the number of positive charges acquired by the sphere being equal to the number of negative charges. Thus the potential assumed by the sphere is greater than that of the undisturbed gas.

If, however, the velocity of the positive ions is approximately equal to that of the negative ions, then the exploring point should attain very nearly the same potential as that of the surrounding gas. For the pressures used in this series of experiments, the velocities of the ions are nearly the same. Thus the error introduced could not have been very great.

A slight error might be introduced if there was an appreciable voltmeter leakage between the point and the power line. The shape of the point also affects the shape of the potential curve to a small degree. The voltmeters used were practically free from leakage, and the work was done during cold, dry weather, so the error introduced from this cause is negligible.

An attempt is being made to formulate the mathematical theory of the corona discharge, and it is hoped that these potential curves will aid in the solution of the problem.

Summary.—The distribution of potential between the electrodes of a corona tube was determined for four sizes of wire, for various pressures and potential differences. From these curves the density of the charge along the radius was derived by means of graphical methods.

In conclusion, I wish to express my appreciation of the suggestions and advice given by Dr. Jakob Kunz, of this laboratory, and to Mr. J. W. Davis and Mr. R. W. Owens for the use of portions of their data on this problem.

PHYSICS LABORATORY,
UNIVERSITY OF ILLINOIS,
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