



XXI. On the forces at the surface of a needle-point discharging in air

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law of force expressed by $4e_1s_1e_2s_2/rR_2^4$. The true significance of the relation of Mills seems to me to be the indication of broad simple dynamical law in the kinetics of electrons forming atoms. These ideas lead at once to the following speculation.

11. *The nature of chemical potential energy.*

If the view proposed in the last section is correct, namely, that a part of the latent heat of vaporization of a liquid is kinetic energy supplied to the electrons of atoms to establish dynamical equilibrium under changed conditions of heterogeneity, it follows that the heat of chemical reactions is energy given out because of changed heterogeneity of the electrons in the reacting atoms. Is it possible that the pairs of electrons of two chemically combined atoms mingle like the molecules of two mixed liquids? Even if such mixture does not take place, the close approach of two different swarms of pairs of electrons may produce instability in the dynamical equilibrium of each and a fall into a new position of equilibrium with evolution of heat in the process. The internal energy of the radium atom is of the type here supposed to reside in all atoms as kinetic energy of the constitutive pairs of electrons.

Melbourne, April 1910.

XXI. *On the Forces at the Surface of a Needle-Point discharging in Air.* By A. P. CHATTOCK, *Professor of Physics in the University of Bristol* *.

THE strength of the field at a spherically ended electrified needle-point may be measured in terms of the pull of the lines of force upon its surface †, if the pull is due to the lines of force alone; a condition which is only strictly fulfilled when the point is not discharging.

In 1897, while attempting to extend this method to a discharging point, I tried the effect of supplying the latter with ions of opposite sign to itself obtained from a second point in its neighbourhood. Some rather interesting effects were observed in air at atmospheric pressure; but as at the time no explanation of them was forthcoming their discussion was postponed, and they remained unpublished.

Recently while looking over the record of the experiments

* Communicated by the Author.

† Chattock, *Phil. Mag.* [5] xxxii. p. 285. Young, *Phil. Mag.* [6] xiii. p. 542.

it occurred to Mr. Tyndall that an explanation of some of the results had become possible in the light of modern theories of discharge. We therefore repeated and extended the old work, and an account of what has been done follows the present paper. This has rendered necessary a discussion of the question how far the pull at a discharging point is due to the field at its surface, and how far to purely mechanical forces brought about by the discharge; and an attempt is here made to estimate the magnitude of these forces, and to show that they may be neglected in the case of our experiments,

Positive Discharge from a Single Point,

When a sharp point discharges positive electricity in air at atmospheric pressure it usually becomes capped with a luminous velvety layer, probably not more than one or two hundredths of a millimetre in thickness. This layer and the air near it is presumably the region in which ionization occurs, and from it therefore ions of opposite signs travel towards and away from the point respectively,

In fig. 1 A represents the surface of the discharging point, much magnified, A and D the limits of the ionizing layer, and A D the axis of the point.

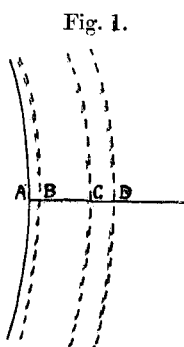


Fig. 1.

Before discharge sets in the field at points along A D will fall off for some distance in nearly inverse proportion to the squares of the distances of these points from the centre of curvature of A; but on the occurrence of discharge some of the lines of force from A will end on ions between A and D, say at B, and others beginning on ions of opposite sign, say at C, will continue on towards the right, with the result that the field is weakened between B and C.

At the same time changes of pressure are set up in the gas by the moving ions; those at C reducing the pressure between A and C, and those at B raising it upon A, so that B C is a region of low pressure as well as of low field intensity.

Take first these mechanical effects of the discharge. To simplify the argument, suppose that there is a single layer of negative ions at B and another of positive ions at C; and let the charge per square centimetre on B be $-\rho$ and that on A $+\sigma$. The pull per square centimetre on A due to the lines of force ending upon its surface is $2\pi\sigma^2$; and if p_1 be

the pressure excess upon A above the atmosphere due to the B ions, and p_2 the corresponding reduction of pressure in AC due to the C ions, the resultant pull per square centimetre on A will be

$$p = 2\pi\sigma^2 - p_1 + p_2,$$

$-p_1 + p_2$ thus representing the change in the pull per square centimetre on the point due to the current discharged from it if the above is a complete account of the pressure-producing part of the process.

The object of what follows is to compare the magnitude of this change with $2\pi\sigma^2$.

Suppose first that the C ions are absent, and consider the effect of p_1 by itself.

The ions in the B layer are attracted by A, and the force of this attraction imparts momentum to them, some of which remains in the ions while the rest is transmitted to the gas through which they move.

Now in the case of ordinary positive point discharge the B ions start very close to A, and it is safe to assume that both parts of the momentum end by being given up to the point in the form of the steady pressure p_1 . p_1 is thus equal to the force per square centimetre to which the B layer is subjected, viz. $4\pi\sigma\rho - 2\pi\rho^2$, and we therefore have

$$\begin{aligned} p &= 2\pi\sigma^2 - 4\pi\sigma\rho + 2\pi\rho^2 \\ &= 2\pi(\sigma - \rho)^2. \end{aligned}$$

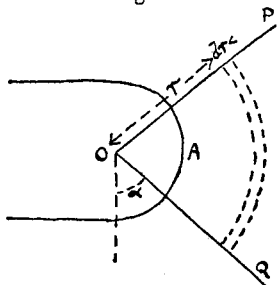
This means that as far as their mechanical effect on the pull is concerned the B ions might just as well have been rigidly attached to A. In other words, if we attempt to calculate the field at the point from the observed pull upon it we shall obtain a value which is less than that of the field at A by the number of lines of force attached to the B ions, and which is therefore due to those lines alone which cross the ionizing region unbroken.

Next consider the suction effect, p_2 , of the C ions.

In ordinary positive point discharge these ions also start very close to the surface of the metal, but they move off to distances which are usually large compared with the size of the point. Except in the region near the point, therefore, the momentum they give to the gas is felt as a pressure on any fixed plate or other bodies there may be opposite the point, and does not sensibly affect p .

Let A in fig. 2 represent the section of a hemispherical point. Near its surface, discharge, when it occurs, will be approximately radial, and may be thought of as filling the cone POQ

Fig. 2.



which has its apex at the centre of curvature of the point.

If f is the field in any spherical layer centred at O and of radius r and thickness dr , the momentum given to this layer per square centimetre per second will be

$$d\mu = f\rho' dr,$$

assuming that ions of one sign only are present, and that ρ' is the volume density of the electricity they carry.

Also, if V is the specific velocity of these ions, C the current from the point, and Ω the solid angle of the discharge cone

$$C = \rho' f V \Omega r^2.$$

Hence

$$d\mu = \frac{C}{V\Omega} \cdot \frac{dr}{r^2}.$$

Suppose now that the sides of the cone are impermeable to gas. $d\mu$ will result in a difference of pressure dp between the two surfaces of the spherical layer such that

$$dp = d\mu;$$

and if r_0 is the radius of the point and the ions are all supposed to start from there, the pressure within the cone at the metal surface will be less than that at a distance r from O by the amount

$$\int_{r_0}^r dp = \frac{C}{V\Omega} \left(\frac{1}{r_0} - \frac{1}{r} \right).$$

With sharp points for which r_0 is a small fraction of a millimetre we may put $r = \infty$, and obtain a value for the integral which is not much greater than if r is a millimetre or so, the result being an upper limit to the value of p_2 for the conditions assumed, viz.

$$p_2 = C/V\Omega r_0.$$

For positive discharge in air at atmospheric pressure I find that the field f_0 at the centre of a hemispherical point when discharge is just ceasing is given by the empirical formula

$$f_0 r_0^{0.45} = \text{constant},$$

where the constant as corrected by Young (*loc. cit.*) is 85 if r_0 is in centimetres and f_0 in E.S. units*.

Hence

$$\sigma = 18/4\pi r_0^{0.45},$$

and

$$\frac{p_2}{2\pi\sigma^2} = \frac{0.0035}{\sqrt{\Omega} r_0^{0.1}} \approx k.$$

The largest current used in the experiments referred to was about 15 microamperes, and the largest value of r_0 was 0.062 cm. V for positive discharge in unit E.S. field is 400 cm. sec.⁻¹, and Ω was roughly 2π judging by the area of the glow.

k for these data is 0.12; and, for the smallest point of radius 0.004 cm., $k=0.14$.

As the area of the point surface at which discharge occurred happened to coincide with that upon which effective pull (*i. e.* pull with a component parallel to the axis of the point) was exerted by the field, these values of k give the ratio of the total axial suction effect of the C ions to the total axial pull of the field on the assumption that both σ^2 and p_2 were similarly distributed over the discharge area.

σ^2 was probably uniform (see below), but as the current density must have varied from zero at the edge to a maximum at the centre of the discharge area, p_2 must have varied in a corresponding manner. The exact law of this variation we have no means of knowing, but we may obtain an idea of the sort of error introduced by assuming p_2 uniform, if we adopt some arbitrary law: say p_2 proportional to $\sin \alpha$ (fig. 2).

Remembering that the total suction normal to the surface of the point will be the same whatever the law, this particular law leads to an axially resolved suction equal to four-thirds that for uniform distribution of p_2 . In other words, if we take

$$k = 0.14 \times 4/3 = 0.19,$$

we shall correct for the want of uniformity in the distribution for this particular case.

* This power of r_0 and the value of the constant were obtained recently, and differ considerably from those given in my original paper (*loc. cit.*). The difference is due to the tapering of the sewing-needles used in the earlier measurements, the effect of which upon the pull was unwarrantably neglected. The later measurements were made upon platinum wires with their ends rounded to hemispheres in the blowpipe.

This means that if we calculate f_0 from P , the total resolved pull on the point, and assume p_2 uniform, f_0 will be 7 per cent. too high; whereas if we assume the sine law it will be 9 per cent. too high; always supposing of course that the values of k obtained above are correct.

Actually, however, they are too high for the following two reasons :—

1. The 400 cm. sec.⁻¹ taken for V represents the specific velocity of fully formed ions. If the C ions do not at once reach their full size, V will be greater than 400 and k proportionately less.

2. A still stronger reason for reducing k is the fact that in actual discharge the surrounding gas is not kept out of the discharge cone as has hitherto been assumed. It is of course really quite free to flow in laterally, and so to prevent the pressure from falling in the region of the point to anything like the extent the above values of k suggest. Instead of producing a slope of pressure, the drag of the ions must be mainly converted into motion of the gas, and the resulting momentum thus transmitted to the plate rather than to the point.

It seems clear, therefore, that as the error in f_0 due to the suction of the C ions is probably not much more than 9 per cent. without either of these reductions, it will be safe to neglect it altogether when they are taken into account.

Consider now the electrical effect of the discharge.

The ionizing layer is traversed by both B and C ions. The B ions are densest at the side of the layer next the point, and the C ions at its other side. The ionizing field will therefore contain lines of force due to both B and C ions, none of which are measured by the pull; and the field calculated in terms of the pull is consequently too small.

It is probable, however, that the ions are swept away so quickly that their lines of force form a negligibly small part of the field at the point. Let t be the thickness of the ionizing layer and τ the average density of the charge on the B ions, close to the metal :

$$\tau = \frac{C}{\Omega r_0^2} \cdot \frac{1}{f_0 V},$$

and $4\pi\bar{\tau}t$ is that part of the field at the metal which is due to the B ions if $\bar{\tau}$ is the average value of τ through the distance t .

The distribution of τ through t is of course unknown, but

as the effect of the B ions will be shown to be small, we may obtain an idea of its magnitude if we assume τ to vary uniformly from its maximum value to zero in passing through the ionizing layer, put $4\pi\tau t = 2\pi\tau t$, and take for f_0 in the expression for τ the value obtained from the pull, viz. $85/r_0^{0.45}$.

Estimating the thickness of the glow as 0.005 cm., a number which is certainly too high, and assuming that this represents t , $2\pi\tau t$ is about 1 per cent. of f_0 for the sharpest point used and much less for all the others, when the current is 15 microamperes.

Whether the glow and the ionizing region are exactly equal in extent is, however, doubtful. As already mentioned, f_0 for discharge is proportional to $r^{0.45}$; the value of f_0 therefore increases rapidly with the curvature of the point, and it is difficult to see why this should be, unless the only effect of the curvature upon the field (viz. the divergence of the lines of force) is able to influence the ionizing process.

But for this to be, the ionizing region must reach far enough beyond the point to feel the divergence of the lines; in other words, it seems as though t should be comparable with the radius of the point in spite of the fact that the luminous region is practically confined to the surface of the metal.

Yet even if t is equal to r_0 , the field of the B ions is less than 3 per cent. of f_0 for the sharpest point and still less for the others; hence when account is taken of the fact that the ions are newly formed and probably travel much faster than we have supposed, there is not likely to be any serious error introduced if f_0 calculated from the pull be taken as the true field at the point.

One other effect of the discharge should be mentioned. The field in the discharge area is presumably constant, so that where discharge occurs σ will also be constant, and Young's correction (*loc. cit.*) for the distribution of σ will be reduced.

When the discharge area is confined to the centre of the point his constant must be used, and

$$f_0 = 1.085\sqrt{8P}/r_0;$$

but for the point under discussion glow was visible over the whole hemispherical end of the point from 15 down to 1 microampere, and possibly lower. In all cases of positive discharge from this point the values of f_0 have been calculated from the formula

$$f_0 = \sqrt{8P}/r_0.$$

It appears from the foregoing arguments that the only force of any importance at the surface of a positive discharging point is the pull of the field upon the metal. This field we should expect to be independent of the current from the point, at any rate for a considerable range of current; and the fact that, as the following table shows, the values of f_0 calculated from the pull are nearly constant thus gives considerable support to those arguments.

In the table are given the values of $\sqrt{8P}$ for various currents from a positive point of radius 0.018 cm. discharging against a flat metal plate 2.2 cm. distant.

$\sqrt{8P}$.	C in microamperes.	$\sqrt{8P}$.	C in microamperes.
7.46	0.19	7.37	13.38
7.42	1.84	7.38	9.39
7.41	3.09	7.38	7.21
7.39	5.45	7.41	4.20
7.39	6.90	7.41	1.64
7.39	8.01	7.43	0.79
7.39	9.59	7.46	0.52
7.38	10.90	7.93	0.0

Negative Discharge from a Single Point.

Ω for negative discharge is usually much less than for positive—several hundred times less in the case of the large point; and the glow projects into the gas to a distance comparable with the diameter of the point instead of being confined to the surface of the latter, its form varying from radial to trumpet-shaped.

That Ω is small means that p_2 is large; but as the area affected by p_2 will be small in the same proportion, these two effects will roughly cancel, and the only important change in the suction of the C ions will be due to the easier access of the outside gas to the cone of discharge, which implies a greater reduction of p_2 for a negative than for a positive point.

As the glow projects into the gas the C ions start, on the average, further from the point, and this also implies a reduction in p_2 .

The B ions, so far as their mechanical effect is concerned, may be expected to behave much as they did for positive discharge, except that their momentum will not now be given up to the point quite so completely.

For these reasons the pull on a negative discharging point is probably quite as little affected by the mechanical forces of the current as that on a positive point.

There is, however, an electrical effect of the negative discharge which requires consideration.

The bounding surface of the discharge cone separates two fields—an outer one composed of lines which pass unbroken from the point into the gas, and an inner one composed partly of unbroken and partly of broken lines.

Suppose that in fig. 2 we pass from A outwards along the discharge cone. The number of lines of force contained by the cone decreases to a minimum near the centre of the ionizing region, and then increases until this region is passed. It follows that if we draw side by side with the discharge cone a second similar cone in the outer field, this second cone must contain, on the average, a number of lines which lies between the maximum and minimum numbers in the discharge cone if the outer and inner fields are to be in equilibrium with one another.

Owing to the narrowing of the discharge area, and the increased thickness, t , of the ionizing region, the field in the latter, unlike that for a positive point, is chiefly composed of broken lines. This would result in P being far too small to give a correct value of f_0 if the discharge area covered the end of the point; but as it is, P is almost wholly due to the lines of the outer field. If therefore we write

$$f_0 = 1.085 \sqrt{8P}/r_0,$$

we shall obtain a number which is less, but perhaps not much less than the value of the field at the bottom of the discharge cone. Except when the current is small, the measurement of f_0 for negative discharge is thus somewhat indefinite.

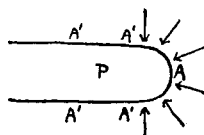
Discharge between two Points.

Suppose that to a positive point P (fig. 3) negative ions are sent from a second point N in its neighbourhood, and that the average field in the ionizing layer remains unaltered. The momentum effect of the N ions on P may be conveniently discussed under two heads.

1. That of N ions which will ultimately reach the hemispherical end of P by the arrow-marked paths.

These will behave like C ions reversed, with this difference—the momentum they impart to the gas keeps to the cones of discharge down which they pass to A much more than with C ions because the sides of the point

Fig. 3.



as well as its ends are receiving ions whereby the pressure of the gas is raised at A'A' as well as at A, and the lateral escape of gas from A is consequently hindered.

The proportionate change (reduction) in p will thus be not much less than that calculated above for C ions travelling in gas-proof cones, viz.

$$k = \frac{C0.0035}{V\Omega r_0^{0.1}},$$

where Ω is 2π and C is that part of the current carried by N ions which reaches the hemispherical end of P. C is thus several times less than the whole current carried to the point by N ions.

The N ions are fully formed when they reach P, so that 400 cm. sec.⁻¹ is now the correct value for V.

In the experiments with two points, both of which were discharging, a current of 15 microamperes meant of course a smaller current carried by N ions, and of this a fraction only arrived at the end of P. If we estimate this fraction at one-fifth and calculate an upper limit for k by assuming that the whole 15 microamperes were carried by N ions, the result is 0.016 for the largest and 0.021 for the smallest point.

The error introduced into f_0 by neglecting this part of the momentum of the N ions is thus of the order of 1 per cent.

2. The remainder of the momentum received by P from the N ions. This is due to the wind set up by the whole of the N ions in passing from N to the conductors connected with P, instead of, as in 1, to the much smaller number which reach the end of P.

It is impossible to calculate the effect of this momentum on P, but an upper limit was obtained by surrounding P with a small cage of which the wires were close enough to shield P electrically, but open enough to allow the wind to pass freely through, the wimshurst being turned at the same rate as in the actual experiments, and the pressure on P measured by tilting the apparatus. Under these circumstances P would be more blown against than without the cage, partly because the cage would attract to itself more of the N ions by reason of its size, and partly because the current from the cage would be less than from P uncovered, and so the wind from N would be less reduced by ions travelling against it.

In no case was the observed force of the wind on P greater than 2 per cent. of the pull when the cage was removed, and

the error in f_0 due to this cause must therefore have been less than 1 per cent.

As to the electrical effect of the N ions, it may be sufficiently described by saying that when they enter the ionizing layer they behave like B ions, and before entering it they play the part of the fixed plate.

And since their mechanical effect on the pull is so small it follows that under the conditions of current and size of point considered above the conclusions already arrived at as to the connexion between f_0 and P for single discharging points of either sign will still hold when N ions are supplied.

Reaction of the Electric Wind.

It may not be out of place here to refer to the assumption sometimes met with in text-books and elsewhere, that the reaction of the electric wind is to be found at the discharging point.

Reaction there must of course be—somewhere—when the wind is started, and its amount must be that of the momentum given per second to the ions; but only an extremely small part of it is to be found at the point itself.

It is true that if a needle with a sharp point and its other end blunt be electrified until the point discharges, it will tend to recede from its discharging end. The electric windmill is a well-known instance of this. But the needle moves because it is pulled more strongly at the blunt than at the sharp end, not because it is pushed back at the latter. If the blunt end be electrically shielded the needle tends to come forward, and to about the same extent that it did before discharge set in; it is the shield which now exhibits reaction by its increased tendency to move backwards.

But the effect on the shield is only part of the wind reaction. When discharge starts the distribution of electricity on all the surrounding conductors changes, and the electrical forces on them alter in such a way that the resultant of these alterations acts in the opposite direction to the wind, and is equal to its reaction.

The wind reaction is thus to be found upon the electrified portions of both electrodes; but the portion which probably feels it as little as any is that part of the point surface at which the discharge actually occurs.

Conclusions.

When discharge occurs at a sharp point in air at atmospheric pressure, the current, dimensions, and other conditions being those considered in this paper, it is possible to calculate the strength of the field in the ionizing region at the surface of the point to within one or two per cent. for a positive and less accurately for a negative point in terms of the mechanical pull upon its surface; and this conclusion holds if the point be supplied with ions of opposite sign to itself from a second point in its neighbourhood.

XXII. *On the Ionizing Processes at a Point discharging in Air.* By A. P. CHATTOCK, *Professor of Physics*, and A. M. TYNDALL, *B.Sc., Lecturer in Physics, in the University of Bristol* *.

[Plate IV.]

IN explaining the phenomena of discharge at sharp points in gases under normal conditions, Sir J. J. Thomson postulates an initial ionization of a few isolated molecules in the gas as a preliminary to the process of discharge.

Suppose a point to be gradually charged with positive electricity in the presence of these isolated ions. The field near its surface is at first unable to do more than clear them away as fast as they are formed; but as soon as it is strong enough to impart to the positives among them sufficient energy to enable these to ionize fresh molecules in their turn, ordinary positive discharge sets in, and a large current may result, accompanied by glow at the point and wind.

In the case of a negative point the field has also to reach a high enough value to enable the initially formed positive ions to form fresh ions; but they now have the alternative of doing this where they bombard the surface of the metal instead of in the gas, and the field required is not necessarily so high as when gaseous molecules are to be ionized.

For both kinds of discharge the supply of positive ions is pictured as kept up by ionization due to negative ions, these having been produced by previously formed positive ions and so on. Both signs of ion have therefore to be able to ionize as each produces the other; and since positive ions require a stronger field for this than negative it is always the field required by the positive ions which has to occur at the point.

* Communicated by the Authors.