
REPORT No. 179

**THE EFFECT OF ELECTRODE TEMPERATURE ON THE
SPARKING VOLTAGE OF SHORT SPARK GAPS**

By **F. B. SILSBEE**
Bureau of Standards

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SUMMARY.

This report presents the results of an investigation carried on at the Bureau of Standards at the request of the National Advisory Committee for Aeronautics to determine what effect the temperature of spark plug electrodes might have on the voltage at which a spark occurred. A spark gap was set up so that one electrode could be heated to temperatures up to 700° C., while the other electrode and the air in the gap were maintained at room temperature. The sparking voltages were measured both with direct voltage and with voltage impulse from an ignition coil. It was found that the sparking voltage of the gap decreased materially with increase of temperature. This change was more marked when the hot electrode was of negative polarity. The phenomena observed can be explained by the ionic theory of gaseous conduction, and serve to account for certain hitherto unexplained actions in the operation of internal combustion engines.

These results indicate that the ignition spark will pass more readily when the spark-plug design is such as to make the electrodes run hot. This possible gain is, however, very closely limited by the danger of producing preignition. These experiments also show that sparking is somewhat easier when the hot electrode (which is almost always the central electrode) is negative than when the polarity is reversed.

OBJECT.

It is a matter of common knowledge in connection with the operation of gasoline engines that engine troubles in general are more manifest on starting than on continued running, and that the machine runs much more smoothly and with less misfiring after it has been "warmed up." It is probable that most of this effect is due to the rise of temperature of the intake manifold and mixture passages, which causes the delivery of a more homogeneous and easily ignited mixture of fuel and air after the engine is warm, but certain effects can not be explained in this way. For example there may be cited a case¹ which occurred while an Hispano-Suiza aircraft engine, having two sets of spark plugs, was being operated in the altitude laboratory of the Bureau of Standards. The plugs of one set were adjusted with very wide spark gaps, and it was found that the engine could not be started using this set of plugs alone, although the magneto was sufficiently powerful to cause a spark to pass over the outside of the spark plug from the terminal to the shell. After the engine had been started on the other set of plugs and allowed to run for a few minutes, it would then operate satisfactorily with the original set of spark plugs having a wide gap.

The experiment just described indicates quite fully that the breakdown voltage of the wide spark gaps in the engine cylinder was for some reason materially reduced after the engine had been in operation, and the increase in temperature of the electrode suggests itself immediately as a possible explanation. The effect of the pressure and temperature of the gas between the electrodes of a spark gap upon the breakdown voltage of the gap has been studied to a considerable

¹ This effect was brought to the writer's attention by Mr S. W. Sparrow of the altitude laboratory of the Bureau of Standards.

extent, the first experiments being probably those of Harris.² More recent work, including that done in 1918 at the Bureau of Standards³ has shown that sparking voltage is a function of the density of the gas only, and is not affected by pressure or temperature of the gas except as these variables may change its density. In the case of the Hispano-Suiza engine cited above, however, the spark plugs would not function at three-fourths load while cold although they did function at full load when hot in spite of the fact that the average density of the gas in the engine cylinder must have been decidedly greater in the latter case. It also seems highly improbable, in view of the exceedingly turbulent motion of the gases in the engine cylinders, that the gas mixture between the spark plug electrodes could be heated materially above the temperature of the rest of the charge. On the other hand, measurements with thermocouples embedded in the central electrode of spark plugs while in operation have indicated average electrode temperatures throughout the engine cycle as high as 900° C. It therefore appeared probable that the temperature of the electrodes might have a direct effect in reducing the sparking voltage of the gap.

HISTORICAL.

Relatively few experiments seem to have been carried out with a view of investigating this effect. Herwig, Macfarlane, Wesendonck, and Jervis Smith⁴ have performed rather qualitative experiments which indicated that there was a decided reduction in sparking voltage under such conditions, but they did not make any quantitative measurements of the temperature of the electrodes nor did they take particular pains to prevent the gas in the gap from being heated by the electrode. In 1902 Stark⁵ suggested in a theoretical paper on ionization by collision, that such an effect would be expected if the electrode heated even a thin layer of the gas adjacent to it in such a manner as to increase the mean free path of the ions in its neighborhood.

DeMuyneck⁶ carried out some detailed experiments from which he concluded that there was a definite lowering of the breakdown voltage with increase in temperature of the electrode which occurred at temperatures lower than that of incandescence. When working with electrodes of large radius of curvature, he obtained no difference in this effect with change of polarity of the heated electrode, but when using fine wires as electrodes he obtained indications of such a polarity effect.

APPARATUS.

In the present investigation a spark gap was set up having for one electrode a brass ball 10 millimeters in diameter mounted on a micrometer screw moving in a fairly heavy metal support which maintained the electrode substantially at room temperature. The other electrode was formed by the tip of a thermocouple junction between wires of chromel (a chromium-nickel alloy) and alumel (an aluminum-nickel alloy). The separate wires were 1 millimeter in diameter and the junction where they were welded formed a roughly spherical lump 2 millimeters in diameter.

During the course of the experiments the tip of the couple became somewhat oxidized and was later filed down to a fairly sharp point. It may therefore be assumed that during the first part of the work with gaps up to 2 millimeters in length the configuration was approximately that of two flat surfaces separated by a gap length not large compared to their radii of curvature. With longer gaps in the first experiments and with all gap lengths in the later ones the configuration approximated a "point-plane" gap. The couple was placed in a small porcelain tube which was wound with a heating coil of chromel wire and the whole construction was imbedded in a heat-insulating cement. The tip of the thermocouple projected from the small furnace thus constructed, as is shown in figure 1. The conduction of heat along the thermocouple wires was sufficient to raise the tip of the junction to 800° C. without dangerously overheating the furnace winding.

² Harris, W. S., *Phil. Trans. of Roy. Soc.*, 124, p. 230, 1834.

³ Loeb, L. B., and Silsbee, F. B., Report 54, National Advisory Committee for Aeronautics.

⁴ Herwig, H., *Pogg. Ann.* 159, p. 565, 1876. Macfarlane, A., *Phil. Mag.* (5) 10, p. 398, 1880. Wesendonck, K., *Wied. Ann.* 30, p. 1, 1887. Jervis Smith, F. J., *Phil. Mag.* p. 48, 477, 1899.

⁵ Stark, J., *Ann. der Physik* 313, p. 837, 1902.

⁶ *Annales Soc. de Bruxelles*, 35, 3 & 4, p. 292, 1910-11.

To insure that the air in the spark gap was heated as little as possible by radiation and convection from the hot electrode, a jet of air was blown upon the gap from the compressed air supply of the laboratory. This jet could be varied in intensity up to that corresponding to a linear velocity of approximately 4,000 centimeters per second. A mica sheet perforated with a hole 2.2 millimeters in diameter was placed as shown in Figure 1 so as to shield the air as much as possible from the heating effect of the furnace. The tip of the thermocouple projected approximately 0.2 millimeter through the hole in the mica shield. The temperatures in the neighborhood of the spark gap were explored by a small auxiliary thermocouple and the results indicated that with a reasonable strength of air blast the bulk of the gas passing through the gap could not be heated more than 15° or 20° C. en route, while if the air blast were shut off entirely the temperature of the gas in the gap would rise more than 100°, depending upon the temperature of the furnace and hot electrode.

Voltage could be applied to this spark gap from three types of source:

(1) Alternating voltage from a step-up transformer could be applied directly to the gap and measured by the voltmeter connected to the primary winding. The wave form of the alternator used in these experiments was substantially sinusoidal so that the crest value of the voltage could be obtained by multiplying the effective value by $\sqrt{2}$.

(2) By inserting a kenotron rectifying tube in series with the secondary of the transformer, and then connecting a condenser in parallel with this combination and with the spark gap, the voltage applied to the terminals of the gap could be rendered substantially constant and of either polarity, as desired.

(3) A typical battery ignition system (Northeast Electric Co. equipment) having a mechanically driven contact breaker in its primary circuit could be directly connected to the spark gap. The breaker was driven at such a speed as to produce approximately 1,000 sparks per minute. The primary circuit was supplied from an 80-volt storage battery through a large series resistance so that the time required for the current to rise to its final value was very short and hence the primary current at "break" and the corresponding secondary voltage were very closely proportional to the mean value of the primary current, which could be read on a D. C. ammeter in the primary circuit. The results obtained with this source of voltage could be directly compared with those from the others by measuring with a crest voltmeter the maximum induced secondary voltage corresponding to various primary currents. Such a comparison is, however, not essential to most of the work since we are interested only in the change in voltage with electrode temperature and not with the absolute magnitude of the voltage.

RESULTS.

Preliminary experiments showed that the sparking voltage at any temperature was independent of the air-blast velocity as it was reduced from the maximum obtainable to a velocity of roughly 700 centimeters per second. When the air supply was shut off entirely, however, so that the air in the gap was stagnant except for the slight natural convection currents arising from the differences of temperature, the sparking voltage was materially reduced. Accordingly a generous flow of air was maintained throughout most of the experiments, but no particular pains were taken to measure this flow quantitatively.

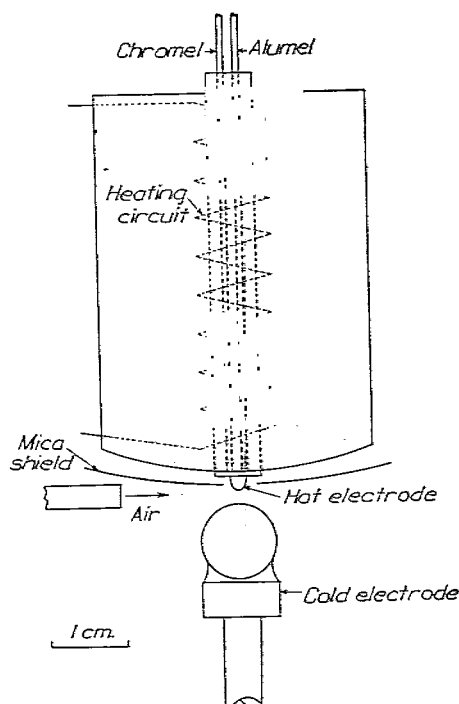


FIG. 1. Experimental arrangement of hot electrode gap.

When the ignition system was used as a source of voltage, it was found that the readings were exceedingly irregular and that at times, even at the high temperatures, no spark could be made to pass regularly even with the maximum available voltage. If the gap was illuminated with ultraviolet light, which was conveniently supplied from a carbon arc, this irregularity was very greatly reduced and consistent readings could be obtained. The effect of this illumination has long been known, and is discussed somewhat below.

The general results may be summarized as follows:

1. With the conditions equivalent to the "point-plane" gap illuminated by the arc, the sparking voltage was definitely greater when the pointed electrode was positive than when it was negative. Both voltages decreased very decidedly with increase in the temperature of the point. This is shown by Figure 2, which gives the actual observed crest voltages, both

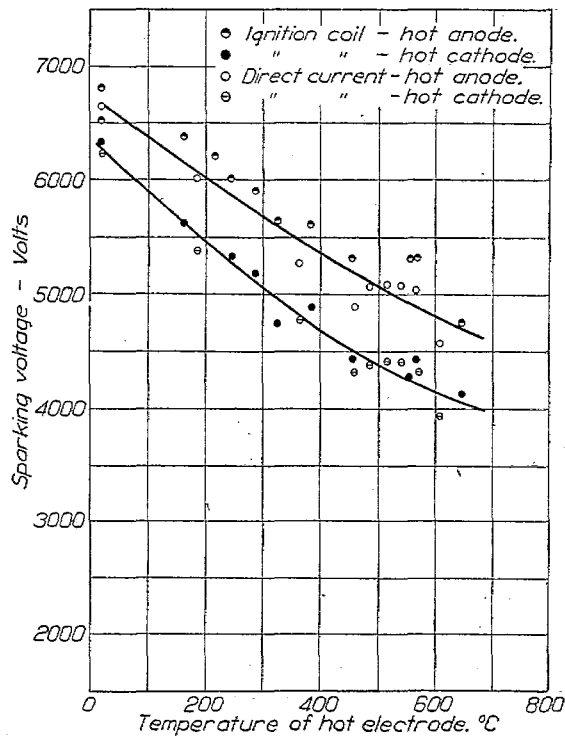


FIG. 2.—Sparking voltages at various electrode temperatures with ultra-violet illumination on point-plane gap.

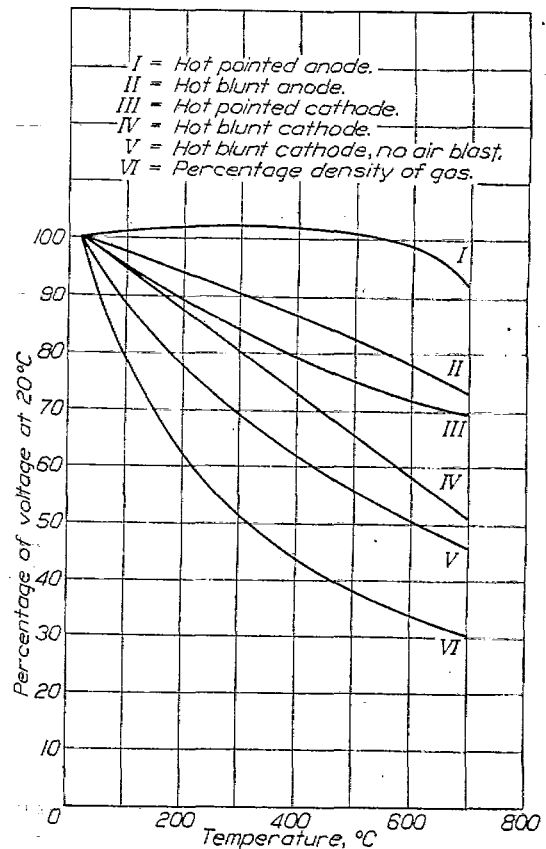


FIG. 3.—Direct current sparking voltage at various temperatures without arc illumination, expressed in per cent of that required at 20° C.

with D. C. and ignition coil sources, at various temperatures and shows the agreement between values with the two sources. The percentage difference between these, however, was nearly constant though it increased slightly as the point was heated.

2. Without the arc light the sparking voltage with the point as cathode was substantially the same (though somewhat less regular) than with the light. The voltage with the point anode, however, was higher and nearly independent of the temperature of the anode up to about 600° C. The data under this condition are plotted in Curves I and III of Figure 3, in which the ordinates are expressed as a percentage of the voltage at room temperature, and have been averaged for several lengths of gap. When the ignition system was used without the arc illumination the results were exceedingly irregular, and at times, even at the higher temperatures, no spark could be made to pass regularly even with the maximum available voltage.

3. With the shorter gaps with the rounded electrode the sparking voltage of the gap when cold was independent of polarity. As the temperature was raised the breakdown voltage on either polarity was decreased, but the change was decidedly greater in the case where the hot electrode was cathode. (See Curves *II* and *IV*, fig. 3.) Cutting off the air blast entirely gave the decidedly lower value of Curve *V*. Curve *VI* shows the density, relative to its density at 20° C., of a perfect gas heated to the temperature of the hot electrode.

EXPLANATION.

The results outlined above may be explained qualitatively on the theory of ionization as developed by Thomson⁷ and Townsend,⁸ provided the following fairly justifiable assumptions are made:

1. There is a thin layer of gas close to (and in the lee of) the hot electrode which is heated nearly to the electrode temperature, and outside of this zone the temperature of the gas drops rapidly but continuously to that of the air blast supply.

2. Casual ions are present in small numbers in the air blast under all conditions but;

3. A very much greater supply of these (of negative sign) is produced at the metal electrodes by the photoelectric action of ultraviolet light or by radioactive material.

The essential feature of the theory of ionization by collision is the postulate that under the electric forces acting on it, a casual ion is speeded up during each free path between two molecular collisions, and if at the end of a path its velocity (or kinetic energy) is sufficiently great it will ionize the molecule with which it collides and produce at the point of collision an additional new pair of ions. Owing to the random distribution of molecules in the gas the duration of the successive free paths of an ion varies greatly and ionization will result only at the end of those large paths for which the product $E\lambda_c$ of the electric field intensity E by the component λ_c of the path λ , parallel to the field exceeds a certain definite value V_c .

The proportion of free paths long enough to produce this ionizing velocity will obviously increase with a decrease in the density of the gas (since a decrease in density increases the length of all the free paths) and with an increase in the applied electric field. We may therefore write for this factor

$$Y = F\left(\frac{E}{\rho}\right) \quad (1)$$

The total number of collisions of the ion with gas molecules as it drifts a distance l under the influence of the field is proportional to l and to the density. Hence the number n of new ions produced will be

$$n = \rho l F\left(\frac{E}{\rho}\right) \quad (2)$$

A mathematical derivation of the form of the function F requires the introduction of various assumptions which need not be discussed here. It seems certain, however, that the effect of ρ in the argument of F is greater than in the coefficient. Definite evidence for this comes from experiments when E and ρ are uniform throughout the region between the electrodes, and it is found that the sparking voltage is increased approximately in proportion to the increase in gas density. In any spark gap there is in general a variation in the electric field intensity E at different parts of the field due to the shape of the electrodes, and in case there are temperature differences, as in the present experiments, there are also variations in ρ from one part of the gap to another. Consequently for any particular value of the total applied voltage V there may be regions in which the argument $\frac{E}{\rho}$ is sufficiently large to produce an appreciable value of n , and such regions will be called "ionizing regions." The critical ionizing

⁷ Thomson, J. J., *Conduction of electricity through gases*. Cambridge Univ. Press, 2d edition, 1906

⁸ Townsend, J. S., *Electricity in gases*, Oxford Univ. Press, 1915.

energy is greater for ions of positive than for those of negative sign, and consequently the argument $\frac{E}{\rho}$ must be greater if ionization by positive ions is to take place. Hence the negative ionizing regions will, in general, be larger than and will include the positive ionizing regions.

A necessary condition, which must be satisfied if a spark is to pass, is that there exist in the gap both positive and negative ionizing regions. This can be seen by consideration of the sequence of events following the entrance of casual ions at point P in the gap shown in Figure 4(a). If regions A and C near the pointed electrodes permit of ionization by negative ions only, then a positive casual ion will produce no new ions at all. A negative casual ion starting at P will move upward and may produce new pairs of ions both in region C and in the part of region A above P . The $+$ ions of these new pairs will move downward but produce no new ions while the $-$ ions will move upward and produce more new pairs. It is evident that all the $-$ ions of these later "generations" will be produced at points above P (or at greater positive potential than the origin of their "parents"), and that ultimately all of the "descendants" of the original ion will be swept out of the field. The net result therefore in such a case is merely the transfer of a finite electric charge between the electrodes (though this may be many times greater than the charge on the original casual ion). If a continuous supply of casual ions is maintained then a steady current will flow proportional to this rate of ion supply; but there will be no tendency toward instability or a spark.

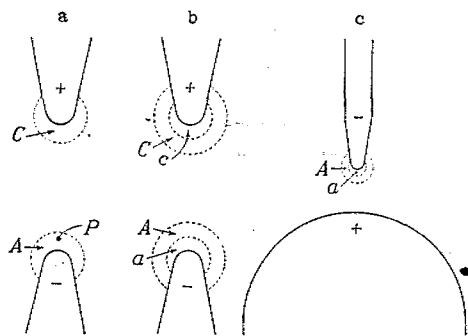


FIG. 4.—Schematic diagrams of ionizing regions in spark gaps.

On the other hand when conditions are as in Figure 4(b) with a positive ionizing region present at a or c as well as the negative region A and C the situation is quite different. An initial $-$ ion introduced anywhere in the gap will produce new pairs of ions above its starting point and the positive ions of these new pairs have opportunity either in c or more effectively in a to produce new pairs and hence new $-$ ions at points below (i. e., at lower positive potential than) the point of origin of the initial casual ion. As a result a new family of ions is started, the process becomes self-sustaining and may develop into a spark.

As a result of the concentration of the lines of force near the electrodes and of the different mobilities of the ions of opposite sign there is usually an accumulation of ions of one sign near the electrode and the space charges arising in this way in some cases (especially with pointed electrodes) so greatly modify the resultant electric field as to produce the stable condition corresponding to the corona or brush discharge. In most cases, however, with blunt electrodes the readjustment of potentials is insufficient to give stability and the ionization progresses to a greater and greater extent until a large current is established across the gap as a true spark. The further course of events depends largely on the characteristics of the source of the applied voltage and the effect of the large spark current on this source.

It will be seen from the above discussion that, neglecting cases of corona, etc., the criterion of whether or not a spark will pass is that the second "generation" of ions produced by a pair of casual ions during the passage of these to their respective electrodes must on the average outnumber the parent generation and be as strategically located for further ionization. The limiting item will be the supply of negative ions produced by positive ions in the region of low positive potential and this number is given roughly by

$$n = \rho l_p F \left(\frac{E}{\rho} \right) \quad (3)$$

where l_p is now the effective depth of the positive ionizing region measured along the lines of force, through which the "average" positive ion moves. If on the average n is greater than

unity a spark will pass, since there will then be a continuous building up of further ionization, while if n is less than unity there will be no spark.

Rearranging equation (3) gives for the sparking voltage, since for a given configuration E is proportional to the total applied voltage V , the equation

$$V = \rho \phi (\rho l_p) \quad (4)$$

where ρ is the density of the gas in the positive ionizing region only.

Applying the above considerations to the various conditions present in the experiments, it appears that the thin film of hot gas postulated in assumption 1 above constitutes the principal ionizing region for both positive and negative ions, since both the diminished gas density and the concentration of field due to the relatively pointed shape of the heated electrode

tend to increase the quantity $\frac{E}{\rho}$ in this region. With no air blast the temperature gradient

from the hot electrode to the cold gas at the other terminal is relatively gradual. A moderately

high voltage will raise the quantity $\frac{E}{\rho}$ above the critical value throughout a considerable

volume as indicated in Figure 4(c) at A and a for $-$ and $+$ ions, respectively, and the breakdown voltage at the higher temperatures will be relatively low as shown by Curve V , Figure 3, though not as low as if the entire gas were heated. With the blast in operation, however, the film of heated air is much thinner and the voltage must be raised so that even with the smaller value of l_p in equation (3) n is still greater than unity. This is shown by Curve IV , Figure 3.

It will be noted from Figure 4(c) that in case the hot electrode is the cathode, all the positive ions produced in the outer part A of the negative ionizing region, together with the casual positive ions from the entire field, pass through the entire positive ionizing region a on their way to the electrode. With the polarity opposite to that shown in Figure 4(c), conditions are quite different. Positive ions will be attracted downward and only those produced in the upper portion of a will (in the lower part of a) be active as ionizing agents. It would therefore be expected that the sparking voltage would be decidedly higher in the latter case. That is very definitely found to be true as shown by comparing Curves II and IV , Figure 3.

Curve I , Figure 3, was taken with a wider gap (3 mm.) than the other observations which gave Curve II , and it appears that with this gap in which the lines of force were mostly concentrated at the very tip of the hot electrode, the positive ionizing region a was so small that it was not effective at all and that the spark occurred only when the voltage was high enough to produce a positive ionizing region at the cold spherical electrode.

The great irregularity in the sparking which was noticed when the gap was supplied from the ignition coil can be readily explained by the absence of any casual ions at the particular instant when the voltage was applied. With the coil used the duration of the voltage peak was about one-two thousandth of a second, while the interval between impulses was one-fifteenth of a second. Consequently the chance of one or more ions being so strategically located at the proper instant as to build up a spark is relatively small, and misfiring would be expected even with very high values of peak voltage.

With an external source of ionization, such as illumination by an arc light, or the presence of radioactive material, the conditions are materially different. The ultra-violet light produces a copious emission of negative ions from the metal electrodes and insures a supply of initial ions whenever the ignition coil applies the voltage, thus greatly steadying the discharge and rendering the succession of sparks quite regular.

The effect of the carbon arc illumination in reducing the sparking voltage with a hot anode is less readily explained. One possibility is that with a hot anode the positive region is so small and without the arc so few casual ions reach it that no spark is produced at a fairly high voltage.

With the cathode illumination, however, a very profuse shower of negative ions will cross the positive ionizing region and produce within it the requisite number of positive ions to establish the unstable sparking condition. In other words the statistical reasoning of the preceding paragraphs becomes applicable only with the presence of the exciting illumination, and without this the gap is subject to the vagaries of the supply of casual ions.

The amount of thermionic emission from the heated electrode can be roughly computed from Richardson's data, but such an estimate indicates that the number of such thermions would be negligible except near the upper temperature limit of the present work. At these higher temperatures the sparking appeared to be slightly more regular even in the dark than at the lower temperatures.

CONCLUSIONS.

This investigation shows quite definitely that the voltage required to produce a spark across a short spark gap is appreciably reduced by raising the temperature of one electrode. This effect can be explained on the usual theory of ionization by collision provided it can be assumed that a thin layer of heated gas adheres to the surface of the electrode. This effect persists and presumably the hot layer is not removed in the presence of an air jet comparable with the turbulence to be expected in the cylinder of an internal combustion engine. The reduction in voltage may amount to 50 per cent at temperatures of 700° C. and is sufficient to reconcile various discrepancies between the sparking voltages observed in such engines and the values computed without reference to this effect.

NOTATION.

- E' = intensity of electric field.
- F' = an unknown function.
- e = total distance drifted by an ion.
- l_p = distance drifted by an ion passing through the positive ionizing region.
- n = number of new pairs of ions produced by one ion in drifting distance l .
- V = voltage applied to spark gap.
- V_0 = ionizing potential of gas.
- Y = fraction of free paths which end by an ionizing collision.
- λ = free path of molecule or ion.
- λ_e = component of free path parallel to electric field.
- P = gas density.
- ϕ = a function inverse in character to F .